Growth and Degrowth in the Use of Material Resources*

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Abstract

The use of material resources in the US grew strongly in the first part of the twentieth century, before beginning to slowly decline in per-capita terms after 1970. This "degrowth" was widespread, occurring across energy inputs, metals, construction inputs, and biological materials. I show that much of this decline came from material-augmenting technical change, spurred on by high energy prices. There is also a significant portion that is due to slowing goods expenditure with rising incomes. Rising foreign trade and the relative increase in intangible investment, however, are largely unimportant. I discuss the possibilities for continued degrowth in material inputs in the coming century.

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1 Introduction

The limits of growth in a world of finite resources is a vitally important question. Economic growth is usually understood to go hand-in-hand with increased resource usage. Given that ultimately, many of the resources we use for production are in finite supply, it is natural to wonder whether our current high living standards are temporary. On the one hand, depleting natural resources may raise their market prices and constrain production. On the other hand, technological change and changing tastes may reduce the need for at least some of these resources, and encourage the use of other, more abundant or renewable resources.

In this paper, I study the use of material resources at the aggregate level in the US economy. I first develop a new data source on the material intensity of the US economy, aggregating and harmonizing data on over 100 raw materials used in economic production, going back to 1850. I first show that use of material inputs rose hand-in-hand with GDP in the early twentieth century, such that the material-output ratio was approximately constant. However, material usage has since decoupled from GDP, beginning around 1970, and even declined somewhat in per-capita terms. This "degrowth" is widespread and apparent for many different materials: energy inputs, metals, construction inputs, and biological materials.

I then develop a novel endogenous growth model which I use to understand the quantitative drivers of this degrowth. The model combines two important elements. First, it allows preferences of consumption goods to be non-homothetic, so that, for example, as consumers get richer their expenditure shares on materially-intensive goods and services fall. Second, it builds on the insights of Jones (2005) to endogenize the direction of innovation over many material inputs. The resulting model remains tractable, but allows for rich interlocking patterns of innovation and expenditure, and is straightforward to estimate using the new data I bring to bear. I use this model to understand the contribution of five forces to material use degrowth: price substitution, directed technical change, expenditure shifts, capital technology changes, and trade. I find the first three are quantitatively significant, but there is little role for the latter two.

Literature Review. Understanding the possibilities of substituting away from raw materials at the economy-wide level is a first-order question in economic growth. Within economics, studies on this topic have historically been theoretical in nature (see, for example, Solow (1974); Dasgupta and Heal (1974); Stiglitz (1980)). Little is known about the long-run aggregate elasticities of substitution across materials of different types, and between materials and factor inputs like capital and labor, particularly when technology is endogenous. Putting empirical discipline on these elasticities is not only important for understanding the future of economic growth in the US., but also for measuring its short and long term resilience in the face of disruption of the supply of key commodities.

Empirical studies of degrowth from other disciplines, such as ecology, have largely downplayed

the possibilities for technical change,[1] and so tended to overemphasize the extent to which growth is limited by depletion of scarce natural resources. Moreover, they have tended to emphasize continuing growth in material usage (Wiedmann et al., 2015; Hickel and Kallis, 2020), a finding that this work challenges. Gierlinger and Krausmann (2012) in particular use much of the same data as this paper, and emphasize the significant growth in material usage since 1870, but not the period of decline since 1970. In contrast, some of the empirical patterns of stabilization and decline for particular inputs in this study were first presented by Ausubel (2015), and later expounded on in McAfee (2019). This work aims to go beyond descriptive analysis, and uncover the structural forces driving degrowth and dematerialization in the US. In addition, this paper does not address degrowth, however defined, at the global level. It is solely focused on the US.

One particular aspect of degrowth has begun to be studied within economics: the transition away from fossil fuels (Desmet and Rossi-Hansberg, 2024; Arkolakis and Walsh, 2023). Hassler et al. (2021) model energy-enhancing technical change, and shows how redirection of innovative inputs away from capital-and labor-enhancing technical change has slowed the growth in fossil fuel usage; see also related work in Kanzig and Williamson (2024). In contrast, this paper is broader and more comprehensive in nature, attempting to measure the use of *all* important materials in production, and the forces driving their usage.

One important new paper with a theory of degrowth is Aghion et al. (2025). They present a model in which non-homothetic demand causes consumers to shift their expenditure towards goods of higher quality, and firms endogenously respond by shifting their innovative efforts towards improving quality vs. increasing quantity. Over time, material inputs stabilize, and GDP continues to grow. This study is complementary in many ways, and focuses more on the production-level determinants of material demand, and mapping to comprehensive data on material usage.

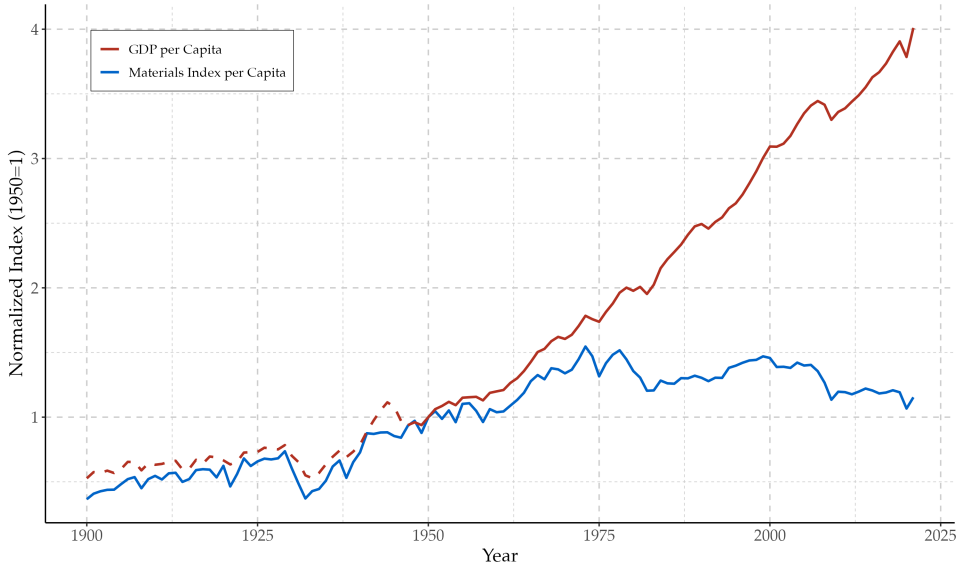
In the next section, I describe the broad facts of degrowth: stagnation and falls in material usage in the United States, while at the same time rapid increases in living standards. In Section 3, I outline a novel endogenous growth model that combines non-homothetic preferences over consumption goods with directed technical change over material usage at the firm level. Section 4 estimates the model, and Section 5 uses it to understand the sources of degrowth in the data.

2 Degrowth in the Data

Degrowth, in the language of Hickel (2020), is "reducing excess resource and energy throughput, while at the same time improving human well-being and social outcomes". In contrast to the body of Hickel's work, and other scholarship in Georgescu-Roegen (1971) and Kallis (2011), such a definition is not incompatible *a priori* with continued growth in GDP. Solow (1956) long ago argued

[1] See, for example, the missed predictions of the seminal Club of Rome model (Meadows et al., 1972; Nordhaus et al., 1992).

Figure 1: Growth in Total Material Usage



Notes: Figure plots the five year moving average of the total annual growth in an index of material usage index. The index is constructed by calculating growth in the total value of resources, and subtracting off a Tornqvist index of price growth, in the same way as in the construction of chain-weighted GDP. GDP data from before 1948 is plotted using the estimates from Bolt and Van Zanden (2025).

that the vast majority of our increase in living standards did not come from an increase in inputs, but from better usage of these inputs to meet human needs.

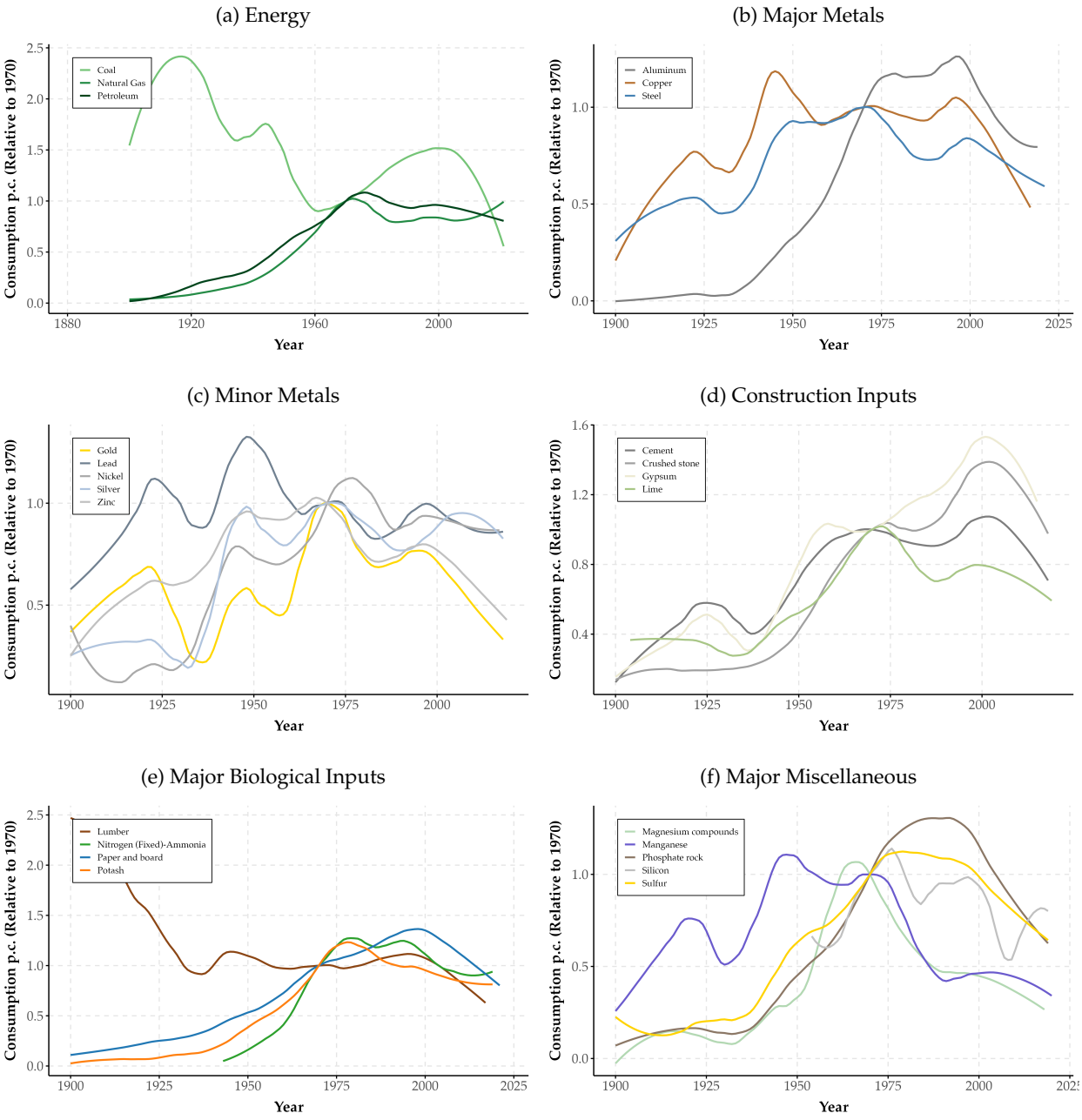
What is less well-appreciated is that degrowth, defined in this way, is actually a reasonable description of the experience on the United States in the last 50 years. In Figure 1 I plot an index of total material consumption in the US. This index is defined as a real chain-weighted measure of total inputs, in an analogous way to real GDP. I compute it using data on the aggregate values of all material inputs in the United States, which I describe below.

Two distinct phases are visible. Material inputs were growing strongly from the start of the 20th century all the way up until 1970. However, after 1970 growth in material resource consumption actually turned slightly negative. Indeed, by 2020, the index value for raw material usage was around 15% lower than in 1970. Meanwhile, GDP per capita has more than doubled, bringing with it all the attendant benefits of longer lifespans, better food and entertainment, and higher-quality housing. It would appear we have been in a period of "degrowth" for some time.

Disaggregating this data supports this broad conclusion. In Figure 2 I plot the consumption of the major components of the materials index by group. A similar pattern is observed for many materials: first, a period of rapid growth in the early 20th century, and then a slowing or outright reversal. The period of growth ends at different points for different materials, but 1970 seems to be a clear turning point. If anything, degrowth of these major inputs accelerates after 2000.

Figure 8 shows this in another way. Of the 30 most important raw material inputs in the US

Figure 2: Resource Usage for Major Inputs



Notes: Figure plots the HP-filtered level of consumption of different resources per capita, and normalizes them relative to the value in 1970.

economy in 1970, 25 now see lower consumption per capita (and in many cases, substantially lower). As an economy, we use less petroleum, steel, lumber, paper, nickel, among a host of other inputs, than we did 50 years ago.

The remainder of the paper seeks to uncover the forces driving these changes. I form five distinct hypotheses, and investigate each of them in the context of a structural model of growth.

One distinct hypothesis that might explain the pattern of moving away from material usage in production has been a period of high and increasing prices for these materials, which could encourage factor substitution. In Figure 9 I plot a Tornqvist index of price growth for material inputs in the US, corresponding to the quantity index in Figure 1, and deflated by the CPI. Real price growth for resources was almost non-existent up until the 1970s and the Arab Oil Embargo, coinciding directly with the period in which material usage rises most rapidly in Figure 1. Since then, aggregate material price growth has been rapid and volatile.

A second, related hypothesis is that this kind of price growth could have induced technical change and innovation to substitute away from the inputs which were appreciating in price most rapidly (Hassler et al., 2021). This is distinct from classical factor substitution in response to a price change, which is usually understood to hold the technical knowledge of firms in the economy fixed. Panel B of figure 9 shows that despite the rapid price growth, the total expenditure share on materials has fallen considerably since 1970.

A third hypothesis is that changes on the demand side could give rise to a change in the mix of goods that are produced, in a way that pushes down the aggregate use of material inputs. It is well known that as economies develop, they shift away from specializing in manufacturing into service production. Services, such as personal care and hospitality, tend to require less resource usage than manufacturing cars and aircraft. Much of the literature on structural change has emphasized the role of non-homotheticities in preferences in driving these changes. Indeed, such expenditure shifts are readily apparent for the US. In Figure 4a I plot Personal Consumption Expenditures in 24 major CPI categories for the aggregate US economy. The rise of medical care spending and spending on financial services is particularly noticeable. At the same time, spending on food at home, new vehicles and motor fuel declines markedly as a share of overall consumption expenditure, suggesting that the resource intensity of the consumer's desired basket may be changing. Of course, overall expenditures rise, so without further analysis it is difficult to conclude whether this could lead to an absolute *fall* in material usage.

A fourth hypothesis relates to changes in expenditure on the investment side. As pointed out by Gomez and Gouin-Bonenfant (2025), the share of intangible capital as a share of overall investment has been rising relentlessly during this period (as can be seen below in Figure 4b), from 10% in 1970 to 29% in 2020. Meanwhile, the ratio of investment to consumption spending has been largely stable, being 26% in 1970 and 26% in 2020. Intangible capital, as the name suggests, tends to be

largely non-physical, consisting of intellectual property and software. It requires skilled labor to produce, but not much in the way of physical resources, even when considering the indirect inputs used in roundabout production. In this way, the capital stock is becoming "lighter" over time, embodying less physical resources as it is replaced and expanded. This, too, may be contributing to the degrowth documented above.

A fifth hypothesis is that changes in trade patterns may contribute to declines usage of raw materials. Expanded trade with China and the developing world is considered key to explain the decline in manufacturing employment in the US (Autor et al., 2013; Pierce and Schott, 2016). Increased imports of manufactured goods, paid for by less materially-intensive service exports and expanded trade deficits, could plausibly explain some part of the degrowth phenomenon.

In the next two sections, I construct a quantitative model of growth and directed technical change with shifting expenditure patterns that can inform the relative strength of each one of these hypotheses.

3 A Theory of Material Usage and Growth

In this section I begin by laying out a simple theory for directed technical change that can encompass many inputs at the production level. I leave considerations of non-homothetic preferences, capital investment and trade to Section

Start with the standard setting: a continuum of firms producing a differentiated variety of an output good. These firms use many raw materials to produce their output; aluminum, petroleum, gold, wood and the like. Each firm has access to a range of production plans which use these materials, and which consist of Leontief maps over input coefficients for each material. They are, in effect, a set of instructions for combining materials, capital and labor in fixed proportions, to produce their differentiated variety. Formally, producing q_t units of the output good requires

$$q_t = min\{a_{lt}l_t,\ a_{kt}k_t,\ a_{1t}x_{1t}, ...,\ a_{Mt}x_{Mt}\},$$

where l_t and k_t are capital and labor inputs, respectively, and x_{mt} are inputs of raw materials, of which there are M. The technical efficiency coefficients a_{mt} differ across production plans within the firm, of which the firm may have many. Some plans may be more intensive in their use of one input (say, steel), and others in another (aluminum). Moreover, some may differ in the efficiency with which they use the fundamental factors of production (capital k_t and labor l_t) to produce output.

I assume that the technical efficiency coefficients, $\tilde{a}_{mt}$, are drawn from independent Pareto distributions before production, given by

$$Pr[a_{mt} \leq a] = 1 - (\frac{a}{\kappa_{mt}})^{-\tilde{a}_{mt}} \quad a \geq c\kappa_{mt} > 0.$$

where c is a normalizing constant. As such, production plans that use any given material more efficiently tend to be rarer and harder to find. To get these plans, the firm must do research. In particular, a firm must hire ν_R units of labor to get an idea draw, which consists of a set of production coefficients for an idea for production which are realized next period. Jones (2005) showed that this particular process gives rise to Cobb-Douglas production functions in expectation for the firm, so that its expected output from N_t ideas is given by

$$\mathbb{E}[q_{t+1}] = \left(\prod_m \kappa_{mt}^{\tilde{a}_{mt}}\right)^{\frac{1}{\sum_m \tilde{a}_{mt}}} \left(N_t k_t^{\tilde{\alpha}_{kt}} l_t^{\tilde{\alpha}_{lt}} x_{1t}^{\tilde{\alpha}_{1t}} \dots x_{Mt}^{\tilde{\alpha}_{Mt}}\right)^{\frac{1}{\sum_m \tilde{a}_{mt}}}. \tag{1}$$

if we let $c = \Gamma(1 - \frac{1}{\bar{a}})^{-1}$ where Γ is the gamma function, and $\bar{a}$ is described momentarily.

I now introduce the notion that firms can search more or less intensively for ideas with better technical coefficients for some materials. That is, they may be interested in improving their efficiency relatively more in one input than another, perhaps due to its expected price the next period. To do so, I assume that the firm can direct share e_{mt} of the research labor ν_R for each good to searching harder in the tail of the idea distribution for that material m. Without research, the efficiency of using any material follows a "default" Pareto distribution with a high shape parameter A (such that efficient ideas are very rare). Research effort works by expanding the search space into the unknown, effectively thickening the tail of the distribution by getting better average draws. I model this as a linear reduction in the Pareto tail coefficient,

$$\tilde{\alpha}_{mt} = A - \phi e_{mt},$$

with the restriction that $\tilde{\alpha}_{mt} > 1$. Increasing search effort towards material m will yield a higher expected technical coefficient for that material in the idea. Defining $\bar{\alpha} \equiv MA - \phi$, we then have

$$\sum_m \tilde{\alpha}_{mt} = \bar{\alpha} \tag{2}$$

for some $\bar{\alpha} > M$, where b_m are fixed. As such, if the firm wants ideas that are on average very efficient in their use of steel, they will end up with ideas that are on average less efficient, in say, the use of labor or capital. The firm chooses a vector $\boldsymbol{\alpha}$ that satisfies (2) each time they hire labor for research. I suppose for the moment that the firm makes one-period research investment decisions, maximizing static profits, and leave to the Appendix the problem of an infinitely-lived firm that chooses a sequence of such decisions. The analysis turns out not to differ substantially, though the exposition is more involved.

Firms must pre-commit to a vector of input purchases, labor employment and capital (which they rent), one period ahead. As such, their problem can be broken into three stages, expressed as

$$\pi_{t+1} = \max_{N_t} \left(\max_{\{\boldsymbol{\alpha_{t+1}}\}} \left(\max_{\{\boldsymbol{x}_{t+1}\}} \mathbb{E}_t[p(q_{jt+1})q_{jt+1}] - \sum_i p_{it+1}x_{it+1} \right) - \nu_R w_t N_t \right),$$

First, given an investment in idea generation N_t, and a direction of research $\boldsymbol{\alpha_t}$, they choose today the vector of inputs $\{\boldsymbol{x}_{t+1}\}$ that will maximize their expected profits from production tomorrow, given (1). Second, given an investment in new ideas, they choose the direction over idea space $\{\boldsymbol{\alpha_t}\}$ subject to (2) in which to search for production plans. Lastly, given these solutions, they choose labor inputs to come up with the number of ideas N_t

Given the result above in (1), in the first stage the firm faces an expected marginal cost of

$$\mathbb{E}_{t-1}[mc_t] = \left(N_t^{1/\bar{a}} \prod_m \kappa_{mt}^{\alpha_m} \right)^{-1} \prod p_{mt}^{\alpha_{mt}} \prod_m {\alpha_m}^{\alpha_{mt}}$$

where p_{mt} is the price of input m at time t, and for ease of notation I define $\alpha_{mt} \equiv \tilde{\alpha}_{mt} / \sum \alpha_{mt} = \tilde{\alpha}_{mt}/\bar{\alpha}$. In the second stage of the problem, the firm works to minimize the expected unit cost next period by choosing its direction of innovation through the vector $\{\tilde{\boldsymbol{\alpha}}_t\}$, subject to (2). The solution takes a closed form, and is given by

$$\alpha_{mt} = \frac{\kappa_{mt}/p_{mt}}{\sum_{m'}(\kappa_{m't}/p_{m't})}. \tag{3}$$

As such, the firm will try and look for ideas that are relatively efficient in their use of inputs that have relatively high prices p_{mt}, and in doing so minimize expenditure shares on these inputs next period. They will do the opposite for factors whose average efficiency will is higher, as represented by the minimum efficiency draw κ_{mt} (recall that for a Pareto distribution, the mean is proportional to the minimum).

I now consider the dynamic evolution of the economy. To start with, I suppose that research in one period spills over to the next, according to

$$\kappa_{mt} = \delta_m \mathbb{E}_{t-1}[a_{mt}],$$

where $\delta_m < 1$. As such, there is a spillover from the average idea quality in the previous period to the minimum of the draws today. Given that with a Pareto, the expected value is indexed to the minimum of the distribution, we have

$$\kappa_{mt} = \delta_m \frac{\tilde{\alpha}_{mt}}{\tilde{\alpha}_{mt} - 1} \kappa_{mt-1} \tag{4}$$

I suppose that raw material are extracted via use of the final good and labor, according to

$$X_{mt} = A_{mt} Q_{mt}^{1-\beta_m} L_{mt}^{\beta_m}$$

where Q_{mt} is a quantity of the final good used in the production, and A_{mt} is a technological shifter that may depend on the total quantity of resources extracted in previous periods. L_{mt} is the amount of labour used in the production of material m.

Finally, labor is in fixed supply within period, and grows at exogenous rate g_n over time. Capital is made solely from the final good, which serves as the numeraire, and depreciates at rate d.

We begin by analyzing technical change on a balanced growth path (BGP). On such a growth path, wages and prices grow at constant rates, as do the factor-specific distribution shifters κ_t^m. In addition, the factor shares of cost given in (3) are constant. We have the following result.

Proposition 1. *There is a unique BGP in this economy. In addition, if $\alpha_m^* > 2/\bar{\alpha}$ for all m, the BGP is locally stable.*

We can use than use the BGP to analyze the direction of technical change in the long-run. In particular, note that optimal input decisions for the extraction of good m imply that

$$X_{mt} = A_{mt}^{\frac{1}{\beta_t}} p_{mt}^{\frac{1-\beta_m}{\beta_m}} L_{mt}$$

In particular define the BGP supply elasticity as $\frac{1-\beta_m}{\beta_m}$. As $\beta_m \to 0$, the material becomes infinitely elastic with respect to its long run price, and it's supply behaviour becomes close to capital (whose long-run price is fixed to the output good price, and so has an infinite supply elasticity). As $\beta_m \to 1$, the ability to expand supply in the long run is limited by the availability of labor, which is growing at constant (possibly zero) rate. We then have the following result.

Theorem 1. *(**Generalized Uzawa Theorem**) Factors in more inelastic long-run supply (higher β_m), and having slower growth in production efficiency (lower g_m^A), see greater long-run factor-augmenting technical change.*

Proof. Note that the price of each material must be growing at rate in the long run

$$g_m^p \equiv \Delta log(p_{mt}) = \beta_m g^w - g_m^A.$$

The result then follows from the stability of factor shares on the long-run BGP, and equation (3). □

Before discussing this result, it is useful to recall the original Uzawa theorem. The Uzawa theorem states that, for a constant returns to scale production function $F(a_t K_t, b_t L_t)$, then if there is a BGP

with long run growth and stable factor shares, then either the production function F is Cobb-Douglas, or the only technical progress is labor-augmenting (growth in b_t only). This can seem somewhat mysterious. It arises from the fact that capital K_t must, in the end, grow at the rate of output on a BGP, since it is produced from the part of output that is not consumed. Since both effective inputs $a_t K_t$ and $b_t L_t$ must grow at the same rate for stable factor shares (if the production function is not Cobb-Douglas), and this rate must be equal to the growth rate of output due to constant returns to scale, the only possibility is that $a_t = 0$.

Theorem 1 shows that this idea generalizes to many factors. Factors which are in perfectly elastic supply, like capital, are produced from output alone and have $\beta_m = 0$ and $g_m^A = 0$. This ensures that there can be, in equilibrium, no effort directed to searching for ideas which augment capital. Once factors become in somewhat inelastic supply, rising wages on the BGP cause their real cost of production to rise in perpetuity. Firms then direct search effort for ideas to combat this cost pressure, leading to technical progress that augments that factor.

How does this translate into factor expenditure shares? Examining equation (4), it is clear that faster growth in factor augmenting technical change can only be accomplished by searching more intensively for ideas that are weighted towards this factor. Given the structure of the economy, this is achieved by *lowering* the long-run expenditure share at the micro level on this material. As such, materials in inelastic supply, or those that are becoming relatively more expensive in the long-run due to technical efficiency of production, see their long-run expenditure shares α_m fall.[2]

To see the impact of scarcity-driven price growth in materials on long-run living standards, we can write the growth of wages as

$$g^w = \frac{1}{\sum_{m \neq l} \beta_m \alpha_m + \alpha_l} \Bigg(\underbrace{\frac{1}{\sigma - 1} g^M}_{\text{Variety/Population}} + \underbrace{\sum_m \alpha_m g_m^\kappa}_{\text{Matieral Use Efficiency}} + \underbrace{\sum_m \alpha_m g_m^A}_{\text{Material Productivity}} \Bigg).$$

As such, there are three sources of growth. The first is the standard effect common to variety models, whereby a larger population induces an increases in variety, which shows up as growth in real living standards. The second is the endogenous improvement of resource-specific productivity, weighted by the BGP expenditure shares for that material. The last is the direct effect of productivity improvements in material production, making it possible to produce more materials with given inputs of labor and the final good.

While the first term is exogenous, the second two are equilibrium objects, given the endogeneity of the expenditure shares and the direction of technical change. To see how they move, consider what

[2]Note this may seem to imply strong predictions about the level of factor shares in the long-run. In particular, equation XX would predict, given steady state growth in wages, that labor should have a lower expenditure share in production that capital, a fact contradicted for most industries in the BEA input-output tables below. However, more broadly conceptualized, the theory can accommodate any initial levels of expenditure shares for capital and labor, by imagining that the Leontief recipes specify combining different types of labor.

happens when it becomes harder to extract materials. This we can think of as a fall in material productivity growth g_m^A on the BGP.

Theorem 2. ***(The Resource Drag)*** *A fall in material production efficiency growth g_m^A for a material m slows economy-wide growth in per-capita output g^w. Moreover, if the BGP resource share of material m is sufficiently large, it also slows growth in total material use efficiency, $\sum_m \alpha_m g_m^\kappa$.*

First, when it becomes harder to extract a particular material, there is a direct effect on living standards through greater scarcity of the material and reduced production. However, there is also an indirect effect that occurs whereby research effort is reallocated to alleviate this scarcity. This pushes the economy towards implementing ideas which are more efficient in the use of the material over time. The direct effect, however, always dominates. Furthermore, if the material has a sufficiently large expenditure share, reallocating research effort towards this material decreases average efficiency growth across materials as well.

Theorem 2 allows us to understand the role of natural resource scarcity in living standards. When a material becomes fundamentally more difficult to produce in the long run, increased research can alleviate some of this pressure on living standards. However, it cannot fully undo this pressure, and growth must slow.

4 Quantitative Model

To take the model to the data, and consider the remaining hypotheses, I now incorporate non-homothetic preferences, trade and changing capital good shares.

I suppose there is a representative consumer with non-homothetic CES (NHCES) preferences over a vector of final consumption goods and services, which is given by

$$\sum_{i=1}^{S} \Omega_{it} (C_{it}/C_t)^{\frac{\sigma-\epsilon_i}{\sigma}} = 1, \tag{5}$$

where i indexes a sector. C_t defines the level of utility implicitly as the solution to this equation (see Comin et al. (2021) for more details). ϵ_i plays the role of an income elasticity, which is allowed to differ across broad sectors, while σ is the elasticity of substitution. As a result, as the consumer gets richer, their expenditure shares going towards, say, resource-heavy manufacturing or intangible personal services may change. Consumers have intertemporal preferences given by

$$U = \sum_{t=0}^{\infty} \beta^t U(C_t, M_t). \tag{6}$$

where M_t is output of a money-type good, and I assume $U_M < 0$. This good can be sold on the world market for an exogenous price p_t^M, and is produced without a resource cost, only a utility

cost. The consumer can also invest in K different capital goods, each of which depreciates at rate δ_k. As such, the budget constraint of the representative consumer is

$$\sum_{i=1}^{S} p_{it}^{C} C_{it} + \sum_{j=1}^{K} p_{jt}^{K}(K_{jt+1} - (1-\delta_j)K_{jt}) = \sum_{j=1}^{K} R_{jt}K_{jt} + \Pi_t + w_t, \tag{7}$$

where p_{it}^{C} and p_{jt}^{K} are the prices of consumption good i and capital good j at time t, respectively. w_t is the wage per unit of labor, which the consumer supplies inelastically, K_{jt} is the stock of capital good j, and Π_t is aggregate profits in the economy. These capital goods are aggregated to production capital and rented out to producers by competitive firms, with a general production aggregator as in

$$K_t = \mathcal{G}_t(K_{jt_j})$$

where the function $\mathcal{G}_t$ is constant returns to scale, and is allowed to vary through time to reflect changes in the usage of capital of different types. In addition, I also introduce trade in each of the sectoral consumption goods. In particular, I suppose that consumption of each sectoral good consists of domestic and foreign varieties, as in

$$C_{it} = \left(\int_{M_i^D} c_{jt}^{\frac{\nu-1}{\nu}} dj + \int_{M_i^F} c_{jt}^{\frac{\nu-1}{\nu}} dj \right)^{\frac{\nu}{\nu-1}}$$

where M_i^D and M_i^F are the sets of available varieties domestically and overseas for sector i. An analogous equation holds for each capital good sectorAs such, foreign purchases add up to foreign income in the aggregate, via

$$\sum_i \int_{M_i^F} p_{jt} c_{jt} dj = \sum_i \int_{M_D^F} p_{jt}(y_{jt} - c_{jt}) dj + p_t^M M_t$$

Both capital goods and consumption goods have the typical CES price indices p_{jt}^{K} and p_{jt}^{C}.

5 Quantitative Analysis

5.1 Data

In this section I describe the data used for the quantitative analysis. The primary database on raw material usage is constructed from several sources. The first is the Historical Statistics for Mineral and Material Commodities in the United States published by the United States Geological Service. It provides data on the historical usage and prices of over 90 non-fuel inputs, including total domestic production, exports and imports. I define usage as "apparent consumption", which add domestic production and imports, and subtracts off exports. This data also contains information on

prices, which I supplement where missing with data from the BLS on producer prices for specific minerals and materials. For data on fuel inputs, particularly petroleum, natural gas and coal, I harmonize data from the US Energy Information Administration Monthly Energy Review (for post 1950-data), and from McDaniel (1963) from 1870 to 1950. Data for lumber and paper is retrieved from the Food and Agriculture Organization of the UN.

Figure 11 in the Appendix shows expenditure by material over time. Petroleum's increasing dominance over the late 20th Century is apparent; it grows from a quarter of expenditure in 1950 to half by 2010. Steel, paper and board and coal remain important throughout, while copper, aluminum and cement fluctuate up and down in their shares of material expenditure. Lumber, the dominant material input by value in 1900, virtually vanishes as a share of expenditure by 2010.

In order to map these data into the economic accounts, I construct a harmonized and "extended" version of the National Input-Output (IO) Tables from the Bureau of Economic Analysis. For the five year intervals from 1972 to 2017, I use the detailed industry IO tables, which have approximately 400 industry and commodity Use and Make Tables. I map each material resource to the corresponding industry which produces it. I then construct Total Requirement Coefficient matrices for each industry, which say, for example, how many cents of gold is required to produce a dollar worth of electronics, taking into account the entire input-output structure of the economy. I am left with a set of matrices whose industry columns sum to unity, and whose rows consist of entries for primary factors (labor and capital), and each one of the material inputs.

To estimate preferences and the demand system above, I use data from the interview component of the Consumer Expenditure Survey (CEX) to measure income-group-specific consumption of goods. The CEX is a nationally representative quarterly survey run by the BLS that provides data on expenditures of US consumers at the household level. Its broad coverage of all components of household expenditure makes it uniquely well-suited to this exercise. As in Del Canto et al. (2025), I group the expenditure categories into 25 groups for which there exists a Consumer Price Index (CPI) price series.

5.2 Estimation and Quantification

The first task is to estimate the demand system in (5). I left each one of the 25 CPI categories represent a good j (e.g. Food Away from Home, New Vehicles etc.). I follow Comin et al. (2021) and let ω_{jt}^n denote the expenditure share of household n on good j. These expenditure shares satisfy

$$log(\frac{\omega_{it}^n}{\omega_{ft}^n}) = (1-\sigma)log(\frac{p_{it}^n}{p_{ft}^n}) + (1-\sigma)(\epsilon_i - 1)log(\frac{E_t^n}{p_{ft}^n}) + (\epsilon_i - 1)log(\omega_{ft}^n) + \zeta_{it}^n + v_{it}^n$$

where ω_{ft}^n is the expenditure share of a base category, which I take to be Apparel. E_t^n is the consumption expenditure of household n, and p_{it}^n is the CPI price index value at time t. $\zeta_{it}^n =$

$log(\Omega^n_{it}/\Omega^n_{ft})$ are relative taste shifters which I project onto household characteristics of education and age, as well as year fixed effects. The identifying assumption is that, after doing so, residual taste shifters are not correlated with household expenditure. The estimated income elasticities are reported in Table (1).

The result broadly conform with intuition. High-income elasticity sectors include Education, Recreation and New Vehicles, while low elasticity sectors are Alcoholic Beverages, Tobacco, and expenditure on motor vehicles that is not direct purchases. One surprise is public transportation, which comes out to be high-income elasticity sector; however, it is dominated by expenditure on airfares. The elasticity of substitution across these CPI categories, σ, is estimated to be 0.216, which perhaps is natural given these are relatively high-level and distinct expenditure categories.

Finally, I back out a measure of aggregate expenditure shifters Ω_{jt} via exactly matching aggregate expenditure by category (as in Figure x, Panel (a)). These expenditure shifters carry time variation in preferences not accounted for by the NHCES demand system. They could be thought of primarily as taste changes across categories as time goes on, or equivalently they may soak up variation coming from quality changes not well-captured by the productivity series used below.

To construct estimates of the production function coefficients for material by industry s and time t, α_{mst}, I isolate low frequency estimates of the Total Requirement Coefficient matrices for each. I then map each one of these industries to a corresponding CPI category, and take expenditure-weighted averages across industry to produce a matrix of Total Requirement Coefficients for each CPI category. This leaves me with 25×98 coefficients across 11 years (1972,1977 etc.). I interpolate the coefficients linearly between IO table publication years, and then extract low-frequency variation via a HP filter to get an annual series. It is important to emphasize that through the lens of the theory developed above, trends in material expenditure shares map directly to the production function coefficients in α_{mst}

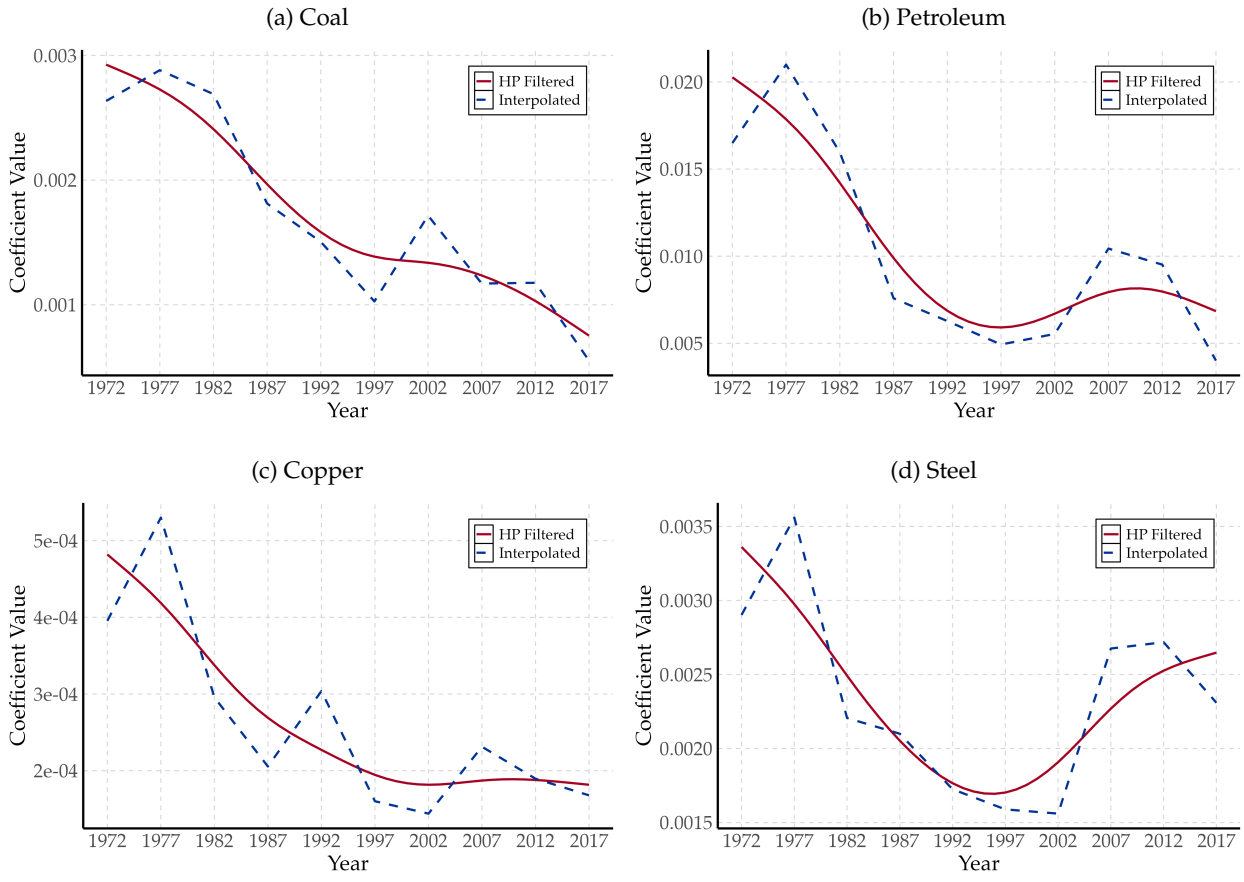
Clear evidence of falling expenditure shares for major material inputs is apparent in several CPI categories. See for example Figure 3, where I plot the estimated production coefficients for Medical Care Services for illustration for four major industrial inputs: petroleum, coal, steel and copper. All four show a secular decline in material expenditure shares, a pattern which is repeated across many CPI categories. However, not all CPI categories show evidence of strong directed technical change over materials. In Figure 12 I plot the same coefficients for New Vehicles. In contrast to much of the rest of the economy, vehicles production does not seem to have become less intensive in its use of petroleum or coal. Steel, which makes up between 5 and 10% of total expenditure on inputs, displays a U-shaped pattern at low frequency, plunging during the 1990s before rising again, perhaps as larger vehicles by weight become increasingly more common.

Table 1: Consumer Demand System Estimation

CPI Category	Interaction	Std. Error	Total Effect	Implied ϵ_i
Education	0.1330	0.0055	-0.0218	0.9722
Information and information processing	-0.1912	0.0033	-0.3459	0.5585
Food at Home	-0.1094	0.0032	-0.2642	0.6628
Alcoholic Beverages	-0.2338	0.0037	-0.3885	0.5042
Personal care	-0.0931	0.0034	-0.2479	0.6837
Shelter	0.0874	0.0032	-0.0673	0.9141
Fuels and utilities	-0.2019	0.0032	-0.3566	0.5449
Household furnishings and operations	0.3424	0.0036	0.1877	1.2395
Medical care commodities	-0.3677	0.0040	-0.5224	0.3333
Medical care services	-0.1358	0.0034	-0.2905	0.6292
Recreation	0.2212	0.0033	0.0664	1.0848
Information technology, hardware and services	-0.2475	0.0037	-0.4022	0.4867
Food Away from Home	-0.0453	0.0032	-0.2000	0.7447
Tobacco and smoking products	-0.3782	0.0046	-0.5329	0.3199
New vehicles	0.2382	0.0040	0.0834	1.1064
Leased cars and trucks	-0.2770	0.0111	-0.4317	0.4490
Car and truck rental	-0.1627	0.0101	-0.3174	0.5949
Motor fuel	-0.1676	0.0032	-0.3223	0.5886
Motor vehicle parts and equipment	-0.3179	0.0037	-0.4726	0.3968
Motor vehicle maintenance and repair	-0.3209	0.0051	-0.4757	0.3929
Motor vehicle Insurance	-0.4493	0.0042	-0.6041	0.2291
Motor vehicle fees	-0.2530	0.0043	-0.4077	0.4796
Public transportation	0.2222	0.0047	0.0674	1.0860
Apparel (baseline)	0.0000	–	-0.1547	0.8025
Unmapped	–	–	1.0000	1.0000
σ	0.216			
Observations (N)	10333573			
Adjusted R2	0.4173			

Notes: This Table reports the results of estimating equation on the Consumer Expenditure Survey for the years 1990-2010.

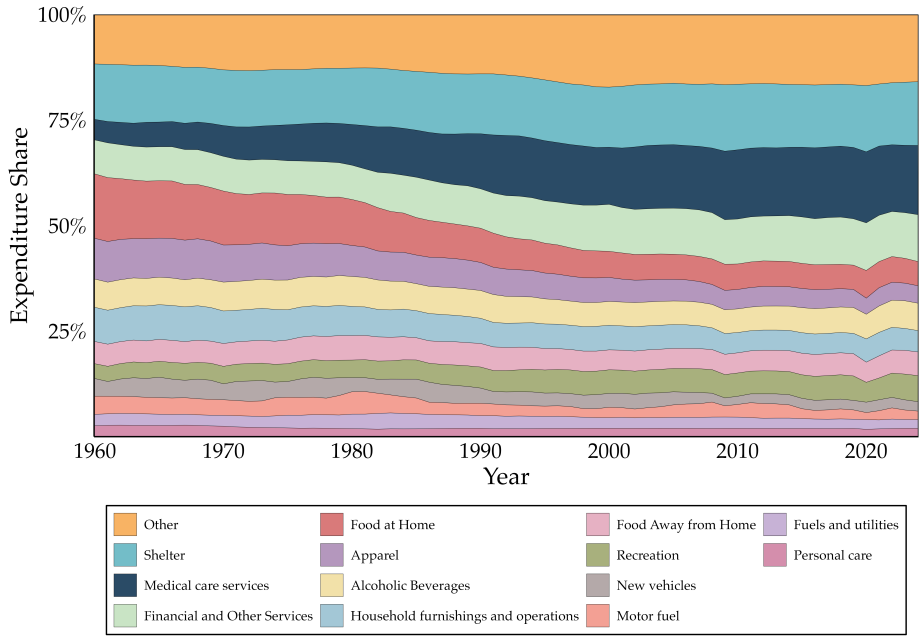
Figure 3: Production Coefficients for Medical Care Services



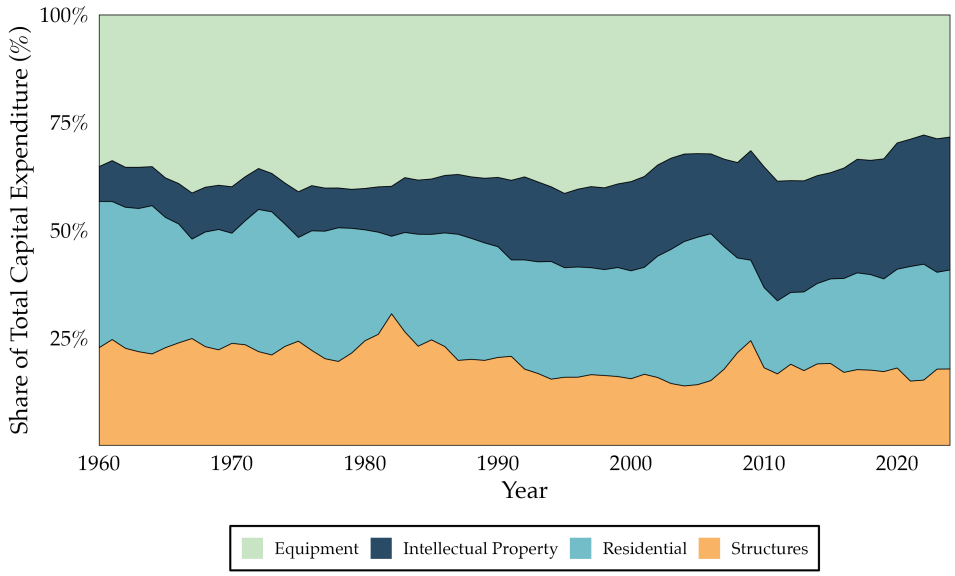
Notes: Figure plots Total Requirement coefficients for Medical Care. Red lines are HP-filtered trend lines.

Figure 4: Expenditure Share Changes

(a) Aggregate Consumption Expenditure Shares



(b) Capital Investment By Type



Notes: Panel (A) of this figure plots the aggregate expenditure shares from NIPA Table 2.4.5 "Personal Consumption Expenditures By Type of Product", aggregated to the 24 major CPI categories used in the model. 10 additional categories are grouped in "Other". Concordance from PCE categories to CPI categories was done manually by the author. Panel (B) plots the aggregate expenditure shares on capital from NIPA 5.2.5. "Gross and Net Domestic Investment by Major Type" for gross private domestic investment.

5.3 Trade

To account for the fact that production and consumption of sectoral goods may not be equal, I introduce international trade into the model. I begin at the level of the Input-Output Tables. For each of the industries that map into producing Personal Consumption expenditure (one of the 25 CPI categories), I record the fraction of output that is exported, and then to aggregate via value weights the fraction of production in each CPI category that is exported. I similarly record imports in each one of these categories, to construct a "Net Foreign Adjustment" Factor by industry and time. I take these forces to be exogenous for the exercise that follows, and do not attempt to model them directly.

Specifically, for each benchmark year t in which an IO table is available, I extract commodity-level export and import values. Let E_{ct} denote the value of exports of commodity c in year t, M_{ct} the value of imports, and Y_{ct} the value of domestic output. I define *total supply* as the sum of domestic output and imports,

$$S_{ct} \;=\; Y_{ct} + M_{ct},$$

and compute the commodity-level export and import shares as

$$s^X_{ct} \;=\; \frac{E_{ct}}{S_{ct}}, \qquad s^M_{ct} \;=\; \frac{M_{ct}}{S_{ct}}.$$

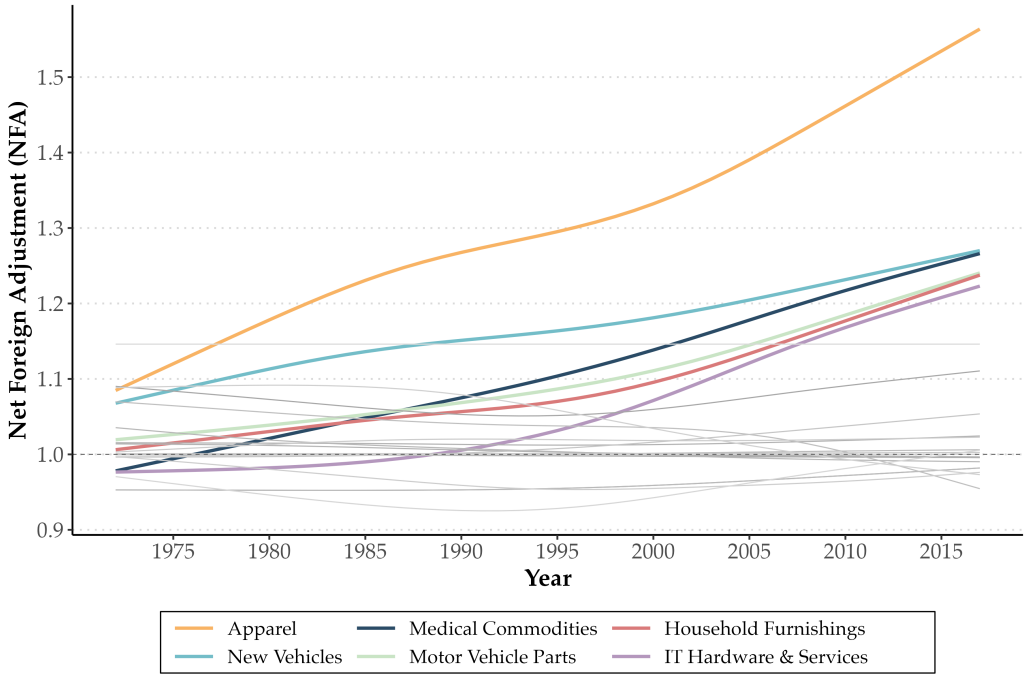
The use of total supply rather than domestic output alone as the denominator ensures that both shares are bounded in $[0, 1]$ and that the accounting identity $s^M_{ct} - s^X_{ct} \leq 1$ is respected. This convention is maintained uniformly across all ten benchmark years.

The IO tables span several decades (1972–2017), and as a consequence are published in several different formats. For the most recent years (2007, 2012, 2017), commodity-level imports are drawn from the BEA Supply table, which reports imports alongside total commodity output at the detailed commodity level. Exports are drawn from the corresponding *Use* table under the final demand column for exports. For the 1997 and 2002 tables, both exports and imports appear as final demand columns within the detailed Use table, published in a long text format. For the 1982 and 1987 tables, I parse the original fixed-width data files released by the BEA: a triplet-format file for 1982 and a wide-format intermediate file for 1987, each with its own bridge table mapping IO commodities to personal consumption categories. The earliest tables (1972 and 1977) are also in a triplet format. In every case, exports are identified by the final demand column code for exports and imports by the corresponding import column, and the total supply denominator is computed identically.

6 Material Usage Changes and Degrowth

The goal of this section is to understand the quantitative importance of five forces in driving the reductions in material use seen in Figures 1 and 2.

Figure 5: Net Foreign Adjustment: Consumption



Notes: This figure shows Net Foreign Adjustment factors for each of the 25 CPI expenditure categories.

6.1 Usage Decomposition

I first provide a useful decomposition of usage changes into a number of components. Let $X_{mt} = \sum_i x_{imt}$ denote total use of material input m in year t, where x_{imt} is the use of material m in producing the output of demand category i. The 29 demand categories consist of the 25 CPI consumption categories plus 4 capital investment categories (equipment, intellectual property, residential structures, and non-residential structures). The log change in total use of each material between a base year (1972) and year t can be decomposed exactly as

$$\ln\left(\frac{X_{mt}}{X_{m0}}\right) = \underbrace{\sum_i w_{im} \ln\left(\frac{D_{it}}{D_{i0}}\right)}_{\Delta_D\text{: Demand Changes}} + \underbrace{\sum_i w_{im} \ln\left(\frac{\varphi_{imt}}{\varphi_{im0}}\right)}_{\Delta_\varphi\text{: Unit Input Requirement Changes}} \tag{8}$$

where D_{it} is real demand (consumption C_{it} for CPI categories, real investment K_{jt} for capital categories), and $\varphi_{imt} \equiv x_{imt}/D_{it}$ is the unit input requirement of material m per unit of demand in category i.

The weights are defined using the logarithmic mean $L(a,b) \equiv (a-b)/(\ln a - \ln b)$:

$$w_{im} \equiv \frac{L(x_{imt}, x_{im0})}{L(X_{mt}, X_{m0})}$$

These weights guarantee an exact decomposition: the demand and technology terms in (8) sum to

the observed log change in material use to machine precision. Physical input use x_{imt} is constructed using Shephard's lemma applied to the Cobb-Douglas cost function: $x_{imt} = \alpha_{imt} \cdot E_{it} / p_{mt}$, where α_{imt} is the cost share from the Total Requirement Coefficient matrices and E_{it} is category expenditure.

The demand contribution can be further decomposed into consumption and investment components:

$$\Delta_D = \underbrace{\sum_{i \in \text{CPI}} w_{im} \ln\left(\frac{C_{it}}{C_{i0}}\right)}_{\Delta_D^{\text{con}}} + \underbrace{\sum_{j \in \text{Cap}} w_{jm} \ln\left(\frac{K_{jt}}{K_{j0}}\right)}_{\Delta_D^{\text{inv}}}$$

I also compute a Net Foreign Adjustment term that captures changes in trade patterns across CPI categories:

$$\Delta_{\text{NFA}}(m,t) = \sum_{i \in \text{CPI}} w_{im}^{\text{con}} \cdot \ln\left(\frac{\text{NFA}_{it}}{\text{NFA}_{i0}}\right)$$

where $\text{NFA}_{it} > 1$ indicates that category i is a net importer in year t.

The unit input requirement is

$$\varphi_{imt} = \frac{\alpha_{imt}}{A_{it}} \cdot \frac{1}{p_{mt}} \cdot \prod_n p_{nt}^{-\alpha_{int}} \cdot \prod_n \alpha_{int}^{-\alpha_{int}}$$

which follows from Shephard's lemma applied to the Cobb-Douglas cost function. Taking logs and grouping terms, I decompose the technology-side contribution into three components:

$$log(\frac{\phi_{imo}}{\phi_{imt}}) = \underbrace{log(\frac{\alpha_{mt}}{\alpha_{m0}}) + log(\frac{\prod_n \alpha_{nt}^{-\alpha_{nt}}}{\prod_n \alpha_{n0}^{-\alpha_{n0}}})}_{\text{Directed Technical Change}} + \underbrace{log(\frac{p_{m0}}{p_{mt}}) + log(\frac{\prod_n p_{nt}^{-\alpha_{nt}}}{\prod_n p_{n0}^{-\alpha_{n0}}})}_{\text{Price Changes}} + Residual \tag{9}$$

The *Directed Technical Change* (DTC) term captures changes in the cost shares α_{imt} --- how the production technology has shifted toward or away from material m. The *Price Changes* term decomposes into own-price effects and cost-weighted price index effects, capturing how relative price movements affect the demand for material m versus other inputs. Each component is weighted by the LMDI weights and summed over all demand categories to obtain the aggregate decomposition.

6.2 Decomposition Results

Figure 6 shows the time path of the decomposition for six major materials. The stacked area charts reveal not only the cumulative contributions, but also their timing. For petroleum, the large negative price contribution occurs sharply in the mid-1970s and early 1980s. For coal, the DTC contribution accelerates after 2005, coinciding with the rapid displacement of coal by natural gas in electricity generation. Several patterns emerge.

First, demand growth is universally positive across all materials. However, due to the non-homotheticities embedded in preferences, demand growth is substantially slower than growth in

GDP per capita (Figure 7 makes this even more apparent).

Second, price effects are the dominant source of degrowth for the energy inputs. Petroleum and natural gas show price contributions of -1.38 and -1.57 respectively, reflecting the large real price increases since the 1970s oil shocks. These price effects alone more than offset the positive demand contributions, explaining why energy use per capita has declined despite continued economic growth. For copper, both price effects (-0.98) and directed technical change (-0.77) are large, making it the material with the greatest overall decline (-1.28 log points).

Third, directed technical change varies substantially across materials. For most materials the DTC term is negative, indicating that production technologies have shifted *away* from these inputs over time. The effect is strongest for copper (-0.77) and coal (-0.36).

Fourth, trade (the NFA term) plays a quantitatively modest role for most materials, with magnitudes generally below 0.10 log points. The small negative NFA contributions for metals (copper -0.07, steel -0.06) are consistent with the shift of manufacturing activity overseas, which reduced domestic demand for material-intensive intermediate goods.

6.3 The Green Transition

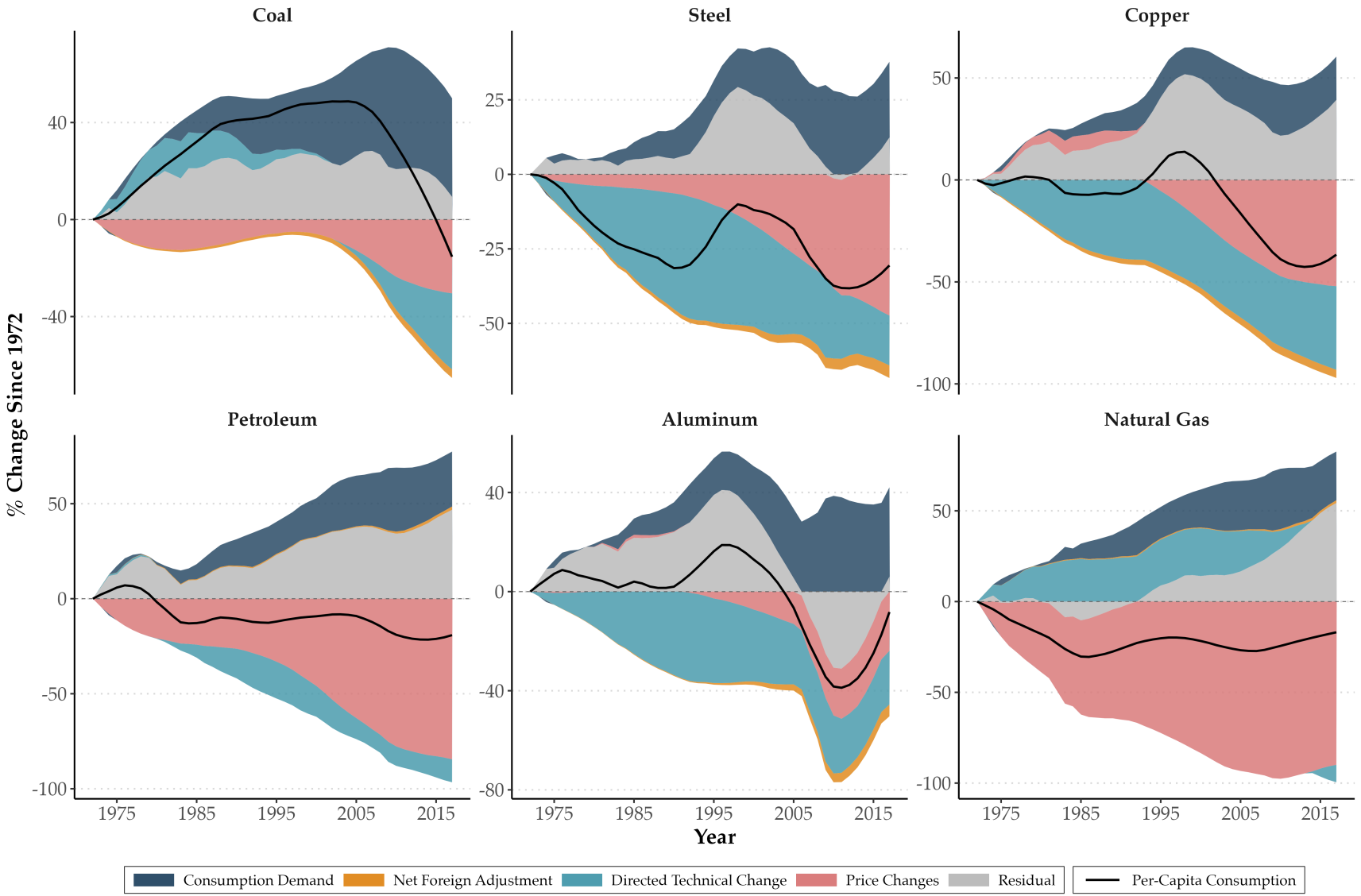
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7 Conclusions

This paper studies the long-run use of material resources in the US economy. I construct a comprehensive dataset covering over 100 raw materials from 1900 to the present, and document that per-capita usage of many major material inputs began to decline after 1970. To understand this degrowth, I develop an endogenous growth model with non-homothetic preferences and directed technical change across many material inputs, and bring it to the data. There are three central findings.

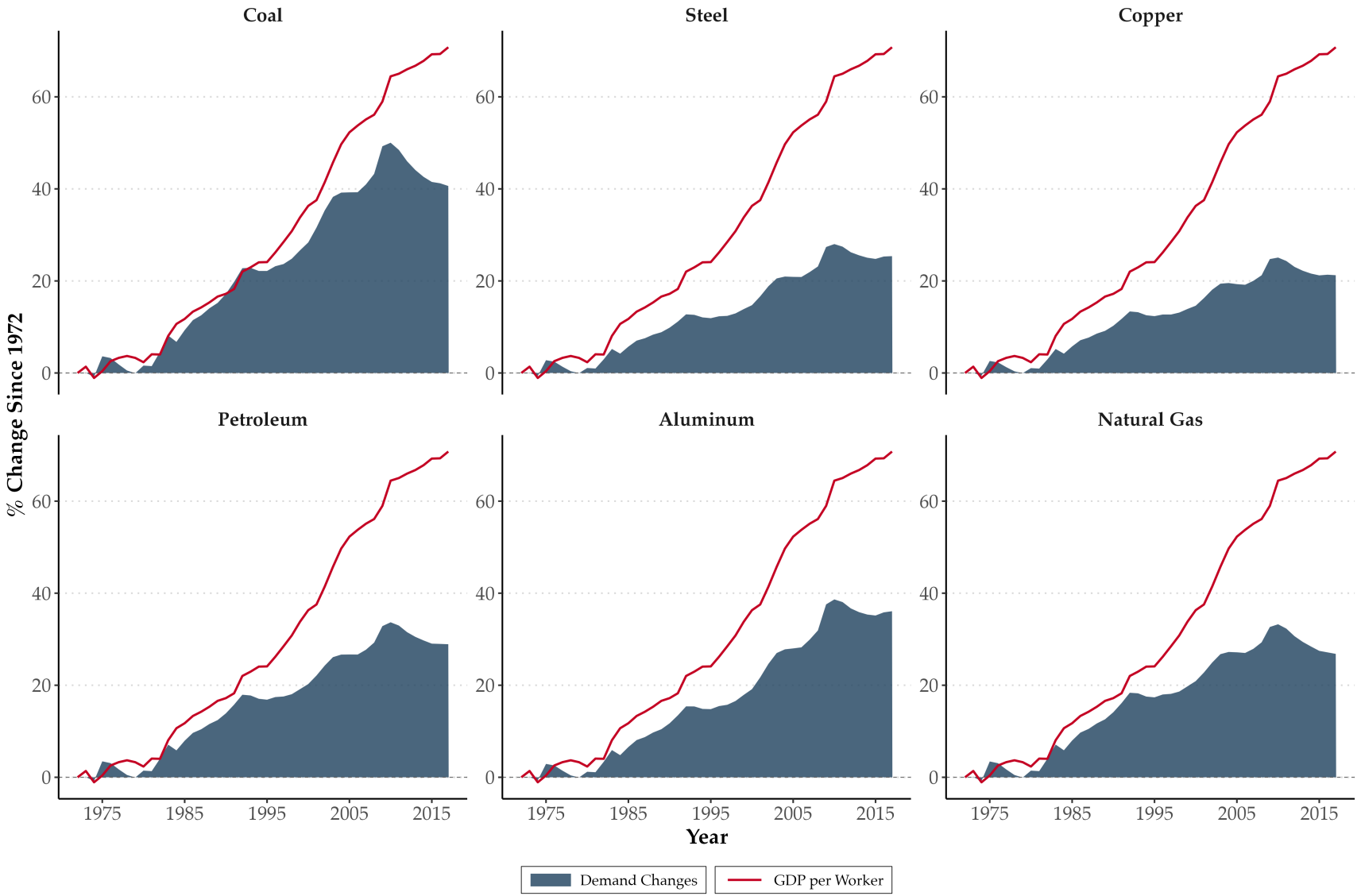
First, price effects were central for reducing the use of energy inputs. The large real price increases following the 1970s oil shocks reduced petroleum and natural gas use by 1.4 and 1.6 log points respectively, more than offsetting the positive pull of demand growth. Second, directed technical change is the primary driver of degrowth for metals. Copper use declined by 1.3 log points, with shifts in cost shares accounting for nearly as much as price effects. Third, demand-side forces pushed material use *up* across the board, but not nearly as fast as overall consumption growth. Thus the composition of demand, and particularly the shift of consumption toward less materially-intensive services, contributed significantly to degrowth for some materials but was quantitatively secondary to supply-side forces. Trade played a very modest role, with the offshoring of manufacturing reducing domestic demand for metals by 5-7 percent.

Figure 6: Decomposition of Material Use, 1972-2017



Notes: This figure shows the LMDI decomposition of the cumulative log change in material use from 1972 for six major materials. Positive areas indicate forces increasing material use; negative areas indicate forces reducing it. The black line shows the total observed log change.

Figure 7: Decomposition of Material Use, 1972-2017



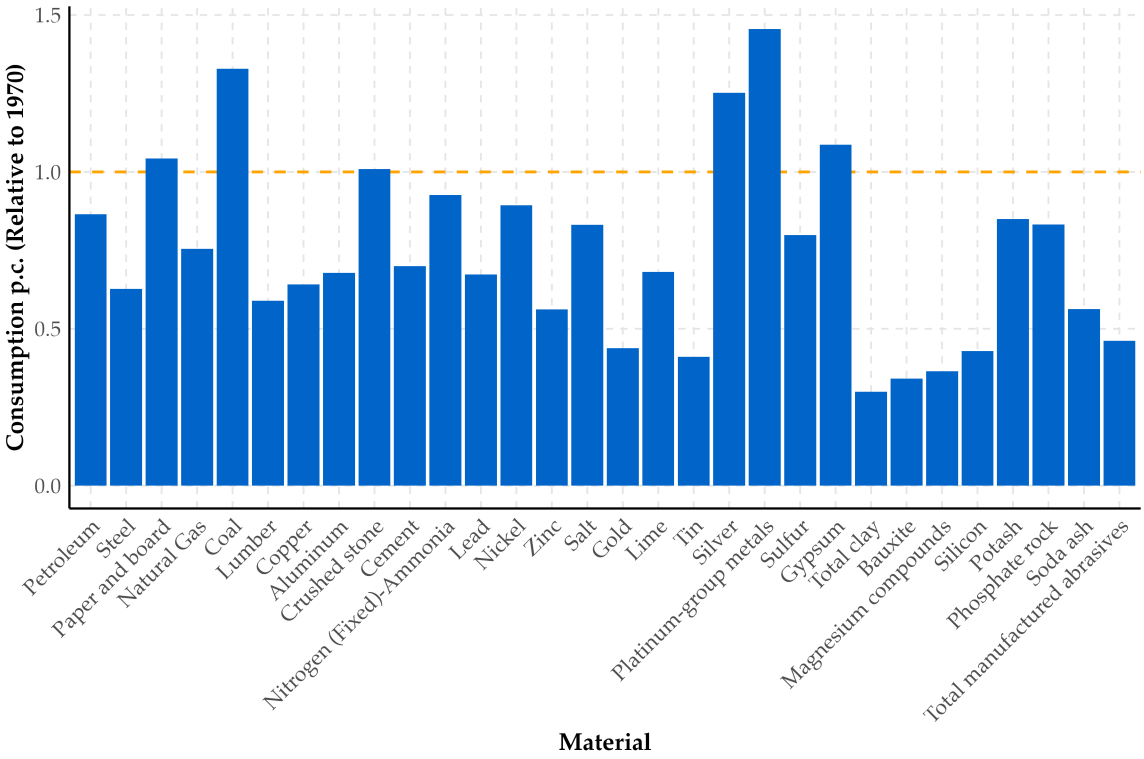
Notes: This figure shows the LMDI decomposition of the cumulative log change in material use from 1972 for six major materials. Positive areas indicate forces increasing material use; negative areas indicate forces reducing it. The black line shows the total observed log change.

These findings speak to the broader question of whether continued economic growth is compatible with declining resource use. The evidence from the US suggests that it is, but not automatically. Degrowth in material use has been driven by specific, identifiable forces: price signals that incentivized substitution, directed innovation that shifted production technologies, and rising incomes that changed the composition of demand. Whether these forces will continue to operate, and whether they will extend to the critical materials required for the energy transition, are important questions for future work.

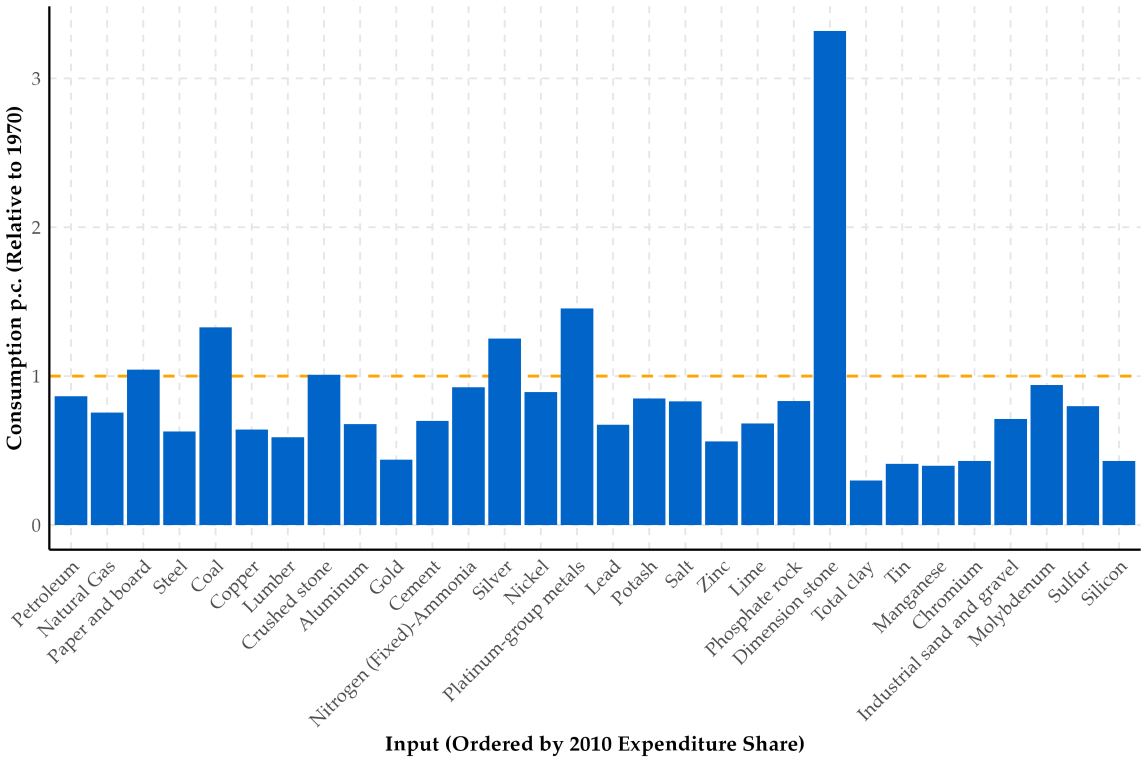
A Appendix Figures

Figure 8: Use of Major Inputs in 2010

(a) Ordered By 1970 Expenditure Share

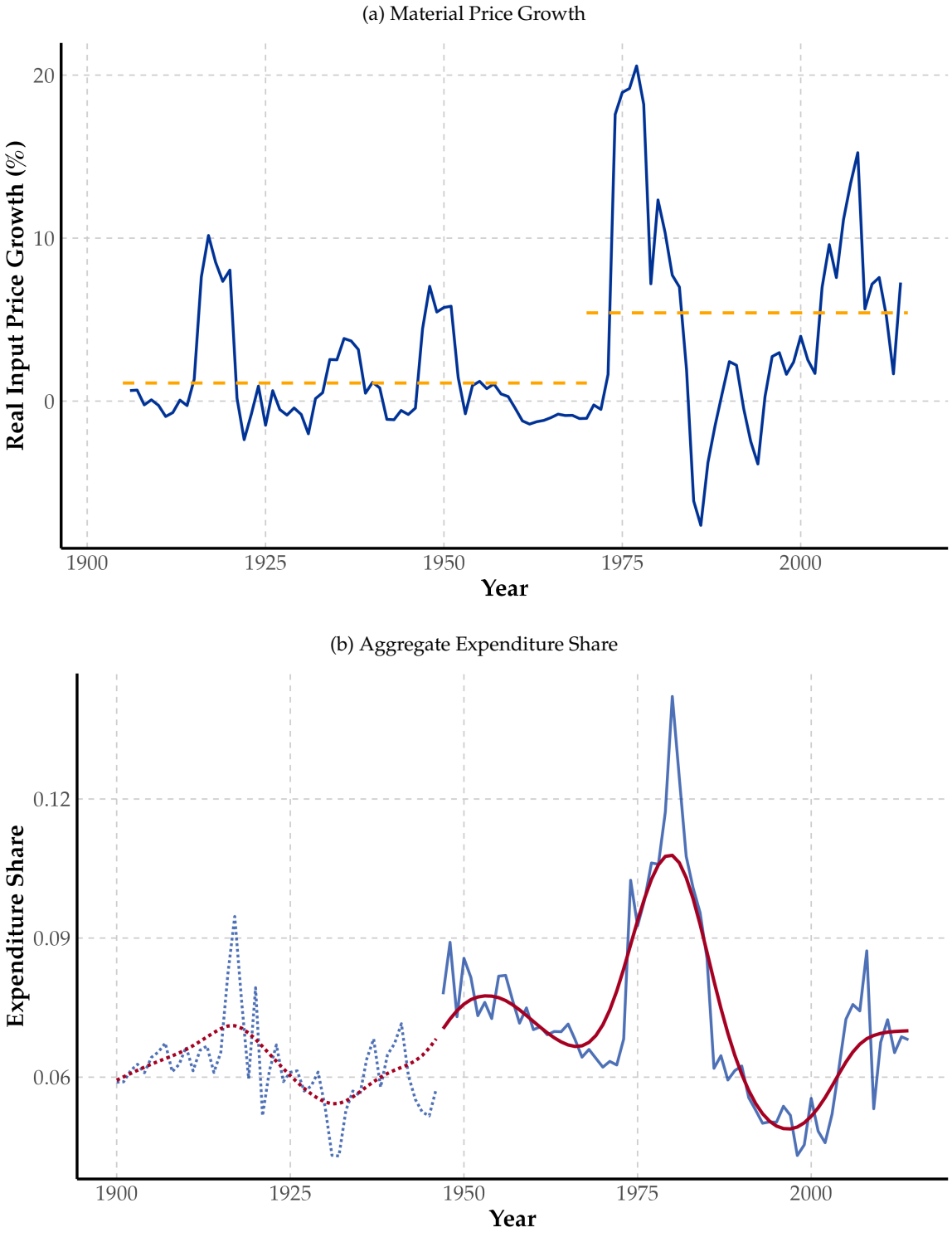


(b) Ordered By 2010 Expenditure Share



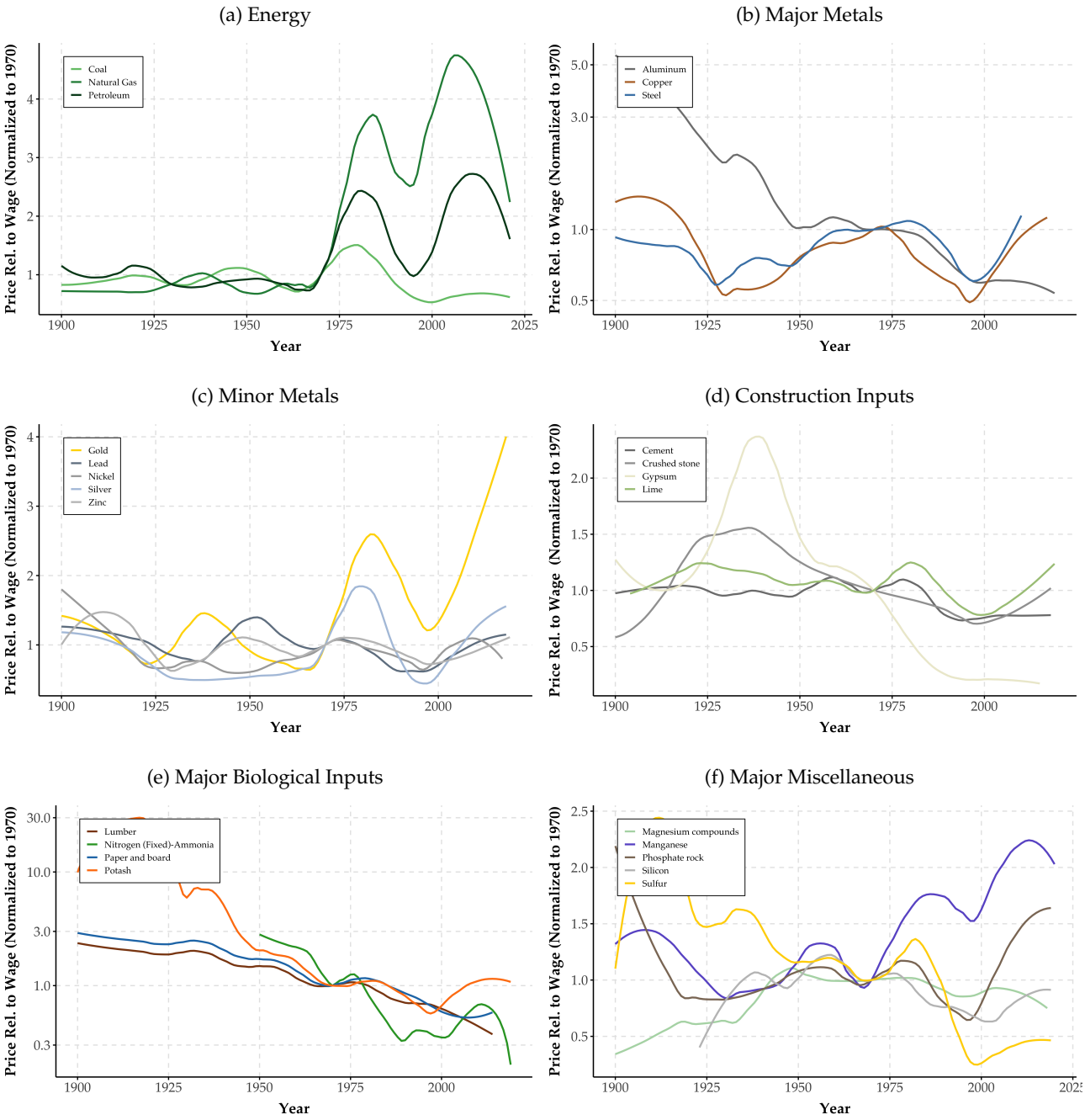
Notes: Panel A plots the level of consumption of different resources per capita in 2010, relative to the value in 1970. The horizontal axis is ordered left to right in terms of expenditure shares in 1970. Panel B repeats this figure with expenditure ordering from 2010.

Figure 9: Price Growth and Expenditure Shares



Notes: Panel A plots the growth in the Tornqvist index of material price growth, subtracting the growth in the Consumer Price Index from the Bureau of Labor Statistics. Panel B plots the value of all material inputs relative to nominal GDP. The blue line is the raw series, and the red line is the HP-filtered trend. Nominal GDP uses data from the Bureau of Economic Analysis after 1947, and before this from the Maddison Project, indicated by the dotted lines.

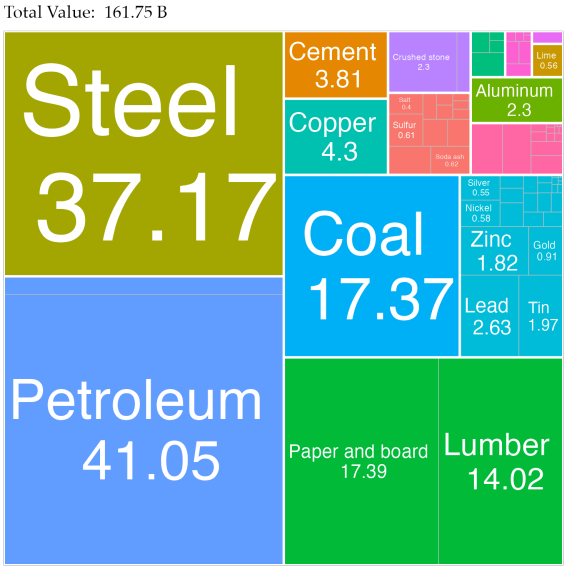
Figure 10: Price Trends for Major Inputs



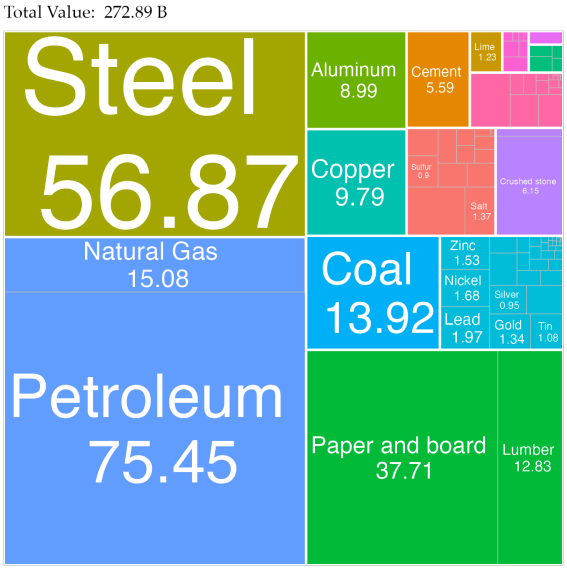
Notes: Figure plots the HP-filtered level of input prices relative to real wages, and normalizes them relative to the value in 1970.

Figure 11: Resource Usage for Major Inputs

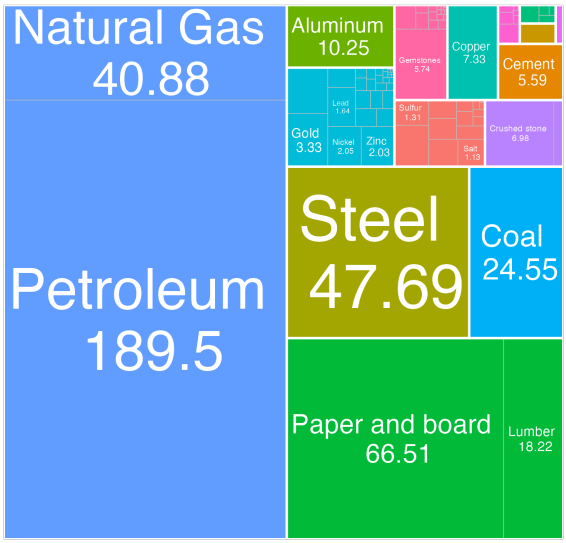
(a) 1950



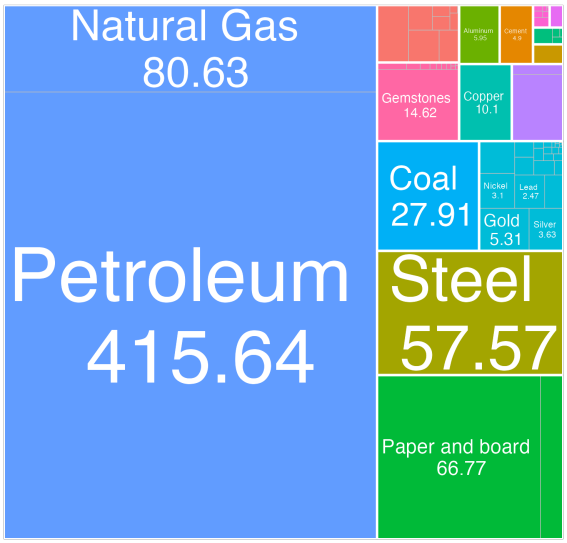
(b) 1970



(c) 1990

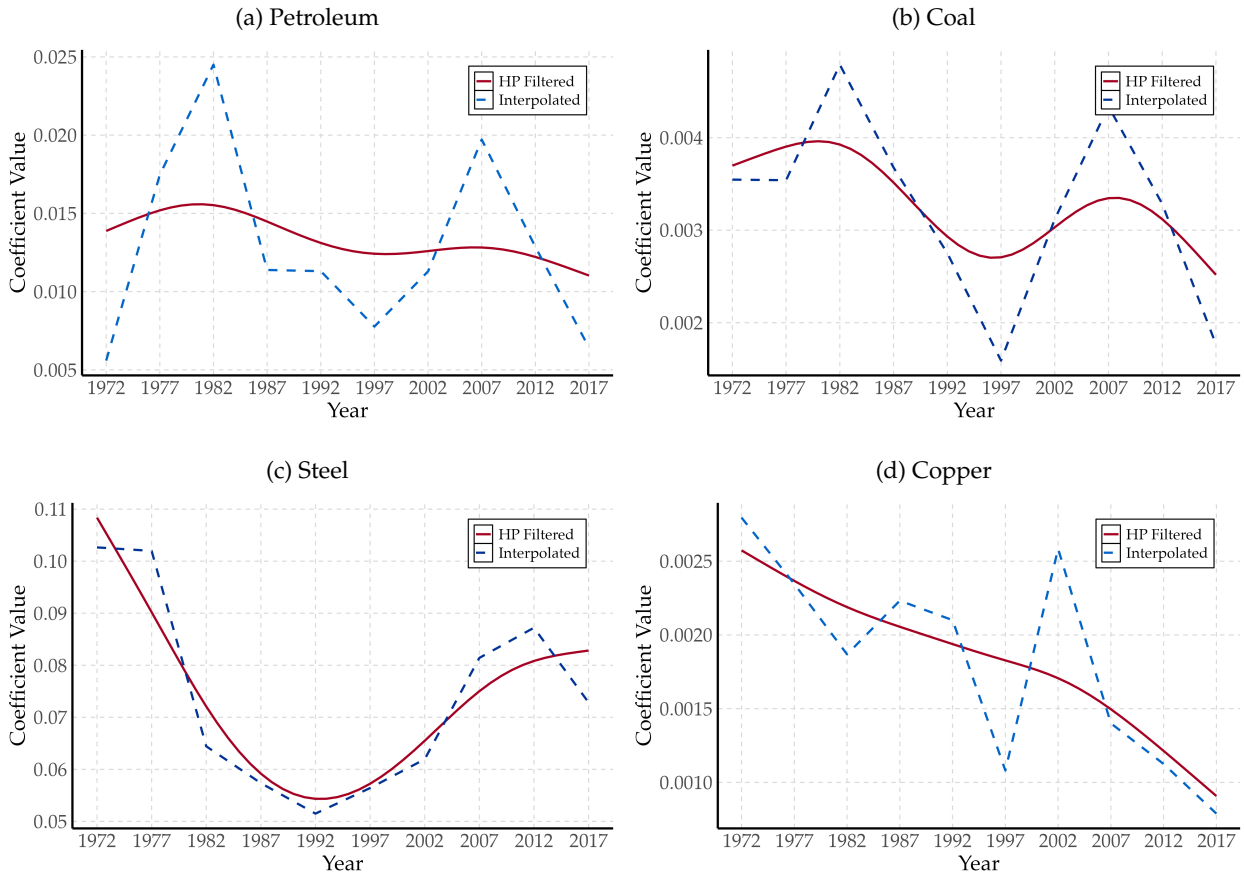


(d) 2010



Notes: Figure plots total expenditure on inputs of different types, in real 1998 dollars.

Figure 12: Production Coefficients for New Vehicles



Notes: Figure plots Total Requirement coefficients for New Vehicles. Red lines are HP-filtered trend lines.

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B Proofs and Derivations

B.1 Equilibrium Characterization

The aggregate price is given by

$$P_t = \left(\int p_t(i)^{1-\sigma} di \right)^{\frac{1}{1-\sigma}},$$

so that, by choosing it as the numeraire, we can write

$$1 = \frac{\sigma}{\sigma - 1} M_t^{\frac{1}{1-\sigma}} \left(N_t^{1/\bar{a}} \prod_m \kappa_{mt}^{\alpha_m} \right)^{-1} \prod_m p_{mt}^{\alpha_{mt}} \prod_m {\alpha_m}^{\alpha_{mt}}$$

Note that the price of each material is simply

$$p_{mt} = \frac{w_t^{\beta_m}}{A_{mt}}$$

So that

$$w_t = \left(\frac{\sigma - 1}{\sigma} M_t^{\frac{1}{\sigma - 1}} N_t^{1/\bar{a}} \prod_{m \neq l} (\kappa_{mt} A_{mt} / \alpha_m)^{\alpha_m} \right)^{\frac{1}{\sum_{m \neq l} \beta_m \alpha_m + \alpha_l}}$$

Now if we define, on a BGP,

$$g_m^A \equiv \Delta log(A_{mt}), \quad g^w \equiv \Delta log(w_t), \quad g_m^\kappa \equiv \Delta log(\kappa_{mt}),$$

and equivalently for prices, we have

$$\begin{aligned} g_m^p &\equiv \Delta log(p_{mt}) \\ &= \beta_m g^w - g_m^A. \end{aligned} \tag{10}$$

Then we can write the growth rate of wages as

$$g^w = \frac{1}{\sigma - 1} \frac{g^n}{\sum_{m \neq l} \beta_m \alpha_m + \alpha_l} + \frac{1}{\sum_{m \neq l} \beta_m \alpha_m + \alpha_l} \sum_m \alpha_m (g_m^\kappa + g_m^A) \tag{11}$$

since $g^M = g^n$ on a BGP, as the growth rate of varieties must be equal to the growth rate of the population. Note also that in this formulation, the number of ideas N_t does not grow. To see this, note that

The profit function is given by

$$\begin{aligned}\pi_t &= \frac{1}{1+r}\frac{1}{\sigma}p^{1-\sigma}Y_t - \nu w_t N_t \\ &= \frac{1}{1+r}Y_t\left(\frac{\sigma}{\sigma-1}\left(N_t^{1/\bar{a}}\prod_m \kappa_{mt}^{\alpha_m}\right)^{-1}\prod p_{mt}^{\alpha_{mt}}\prod_m {\alpha_m}^{\alpha_{mt}}\right)^{1-\sigma} - v w_t N_t.\end{aligned}$$

Optimal N_t is thus given by

$$N_t = \frac{(\sigma-1)/\bar{a}}{1+r}\left(\left(\frac{Y_t}{v w_t}\right)\left(\frac{\sigma}{\sigma-1}\prod_m \kappa_{mt}^{-\alpha_m}\prod p_{mt}^{\alpha_{mt}}\prod_m {\alpha_m}^{\alpha_{mt}}\right)^{1-\sigma}\right)^{1-(\sigma-1)/\bar{a}}$$

Labor market clearing requires

$$L_t^P = \int l_i di$$

and where labor demand derived from first order condition

$$k_t = \frac{w_t \alpha_{kt}}{r_t \alpha_{lt}} l_t.$$

$$y_t = \left(\prod_m \kappa_{mt}^{\tilde{a}_{mt}}\right)^{\frac{1}{\sum_m \tilde{a}_{mt}}}\left(N_t k_t^{\tilde{\alpha}_{kt}} l_t^{\tilde{\alpha}_{lt}} x_{1t}^{\tilde{\alpha}_{1t}}\ldots x_{Mt}^{\tilde{\alpha}_{Mt}}\right)^{\frac{1}{\sum_m \tilde{a}_{mt}}}$$

can be written

$$\begin{aligned}y_t &= N_t^{1/\bar{a}}\prod_m \kappa_{mt}^{\alpha_m}\prod_{m\neq l} p_{mt}^{-\alpha_{mt}}\prod_{m\neq l}{\alpha_{mt}}^{\alpha_{mt}}{\alpha_l}^{-\sum_{m\neq l}\alpha_{mt}} w^{\sum_{m\neq l}\alpha_{mt}} l \\ &= N_t^{1/\bar{a}}\prod_m \kappa_{mt}^{\alpha_m}\prod_m p_{mt}^{-\alpha_{mt}}\prod_m {\alpha_{mt}}^{\alpha_{mt}}\frac{w}{\alpha_l} l\end{aligned}$$

so

$$\begin{aligned}L_t^P &= \int \frac{y_i}{\alpha_l N_t^{1/\bar{a}}\prod_m \kappa_{mt}^{\alpha_m}\prod_m p_{mt}^{-\alpha_{mt}}\prod_m {\alpha_{mt}}^{\alpha_{mt}}} di \\ &= \int \frac{p^{-\sigma}Y}{\alpha_l N_t^{1/\bar{a}}\prod_m \kappa_{mt}^{\alpha_m}\prod_m p_{mt}^{-\alpha_{mt}}\prod_m {\alpha_{mt}}^{-\alpha_{mt}} w} di \\ &= M_t\int p^{1-\sigma}\frac{Y}{\alpha_{lt} w_t} \\ &= \frac{Y_t}{\alpha_{lt} w_t}\end{aligned}$$

So that labor gets a constant share of gross output on the BGP. Then we can write the number of

ideas as

$$N_t = \frac{\sigma/\bar{a}}{1+r}\left(\left(\frac{\alpha_l L_t^P}{v}\right)\left(\frac{\sigma}{\sigma-1}\prod_m \kappa_{mt}^{-\alpha_m}\prod p_{mt}^{\alpha_{mt}}\prod_m {\alpha_m}^{\alpha_{mt}}\right)^{1-\sigma}\right)^{1-\sigma/\bar{a}}$$

B.2 Proof of Proposition 1

Stability of factor shares implies that

$$g_m^\kappa - g_m^p = \gamma$$

for some invariant $\gamma \in \mathbb{R}$ for all materials m. Recall that price growth for each material satisfies

$$g_m^p = \beta_m g^w - g_m^A$$

Combining these yields

$$g_m^\kappa = \gamma + \beta_m g^w - g_m^A$$

Rewrite (11) as

$$Dg^w = \frac{g^n}{\sigma-1} + \sum_m \alpha_m(\beta_m g^w + \gamma),$$

where

$$D \equiv \sum_{m\neq l} \beta_m \alpha_m + \alpha_l,$$

which implies that

$$\gamma = -\frac{g^n}{\sigma-1},$$

and is fixed on any BGP given g^n is taken to be exogenous.

Now define

$$h(u) = log(\frac{\delta u}{u-1}) \text{ for } u > 1$$

with $h'(u) = \frac{1}{u} - \frac{1}{u-1} < 0$ for $u > 1$. Then, from (4) on the BGP, we have $g_m^\kappa = h(\bar{\alpha}\alpha_m)$. Given that, we have

$$h(\bar{\alpha}\alpha_m) = \gamma + \beta_m g^w - g_m^A$$

defines $\alpha_m(g^w)$ as a continuous, decreasing function for each α_m. As $g^m \to \infty$, we have $\bar{\alpha}\alpha_m \to 1$, and as $g^m \to -\infty$ we find $\bar{\alpha}\alpha_m$ to ∞. The constraint on the BGP is that input shares must sum to 1, so we have

$$\sum_m \alpha_m = 1. \tag{12}$$

The LHS of (12) diverges to ∞ as $g^w \to -\infty$, and is a continuous, decreasing function. It converges to $\frac{M}{\bar{\alpha}} < 1$ as $g^w \to \infty$. Hence there is a unique solution for g^w that satisfies (12) on the BGP.

To analyze the stability of the system, note that we have the following laws of motion for technology and wages, expression in growth rates

$$g_{mt}^{\kappa} = \delta_m \frac{\alpha_{mt}\bar{a}}{\alpha_{mt}\bar{a} - 1} - 1$$

$$g_t^w = \frac{1}{\sigma - 1} \frac{g^M}{\sum_{m \neq l} \beta_m \alpha_{mt} + \alpha_{lt}} + \frac{1}{\sum_{m \neq l} \beta_m \alpha_{mt} + \alpha_{lt}} \sum_m \alpha_{mt} (g_{mt}^{\kappa} + g_{mt}^{A})$$

$$\alpha_{mt} = \frac{\kappa_{mt} / p_{mt}}{\sum_{m'} (\kappa_{m't} / p_{m't})}$$

$$g_{mt}^{p} = \beta_m g_t^w - g_{mt}^{A}$$

Linearization. Let $\hat{\alpha}_{mt} \equiv \alpha_{mt} - \alpha_m^*$ with $\sum_m \hat{\alpha}_{mt} = 0$. Since $\alpha_{mt} = z_{mt} / \sum_{m'} z_{m't}$ and the log growth rate of z_{mt} is $g_{mt}^z = h_m(\bar{\alpha}\alpha_{mt}) - \beta_m g_t^w + g_m^A$, a first-order expansion around the BGP gives

$$\hat{\alpha}_{mt+1} = \hat{\alpha}_{mt} + \alpha_m^* \left[\tilde{g}_{mt} - \sum_{m'} \alpha_{m'}^* \tilde{g}_{m't} \right], \tag{13}$$

where $\tilde{g}_{mt} \equiv g_{mt}^z - \gamma^*$ is the deviation from the BGP growth rate. Linearizing:

$$\tilde{g}_{mt} = -\lambda_m \hat{\alpha}_{mt} - \beta_m \hat{g}_t^w, \qquad \lambda_m \equiv \frac{1}{\alpha_m^* (\bar{\alpha}\alpha_m^* - 1)} > 0, \tag{14}$$

using $h_m'(u) = -1/[u(u-1)]$, which is independent of δ_m.

Proof. It remains to express $\hat{g}_t^w$ in terms of $\hat{\boldsymbol{\alpha}}_t$. From the wage equation (equation (10) of the paper), $g_t^w = N_t / D_t$ where $N_t = g^n/(\sigma - 1) + \sum_m \alpha_{mt}(g_{mt}^{\kappa} + g_m^A)$ and $D_t = \sum_{m \neq l} \beta_m \alpha_{mt} + \alpha_{lt}$. A standard linearization yields $\hat{g}_t^w = (\hat{N}_t - g^{w*} \hat{D}_t)/D^*$. Using $\sum_m \hat{\alpha}_{mt} = 0$, the numerator perturbation is $\hat{N}_t = g^{w*} \sum_m \beta_m \hat{\alpha}_{mt} - \Lambda_t$ where $\Lambda_t \equiv \sum_m \alpha_m^* \lambda_m \hat{\alpha}_{mt}$. Meanwhile, $\beta_l = 1$ and $\sum_m \hat{\alpha}_{mt} = 0$ together imply $\sum_m \beta_m \hat{\alpha}_{mt} = \hat{D}_t$, so the g^{w*} terms cancel:

$$\hat{g}_t^w = -\Lambda_t / D^*, \qquad D^* = \sum_{m \neq l} \beta_m \alpha_m^* + \alpha_l^* = \bar{\beta} \equiv \sum_m \alpha_m^* \beta_m. \tag{15}$$

Substituting (14)–(15) into (13) and writing $\eta_m \equiv \beta_m / \bar{\beta}$, we obtain the linear system $\hat{\boldsymbol{\alpha}}_{t+1} = \mathbf{A}\hat{\boldsymbol{\alpha}}_t$ where

$$\mathbf{A} = \mathbf{D} + \mathbf{u}\mathbf{v}^{\top}, \qquad \mathbf{D} = diag(d_1, \ldots, d_M), \tag{16}$$

with $d_m = 1 - \alpha_m^* \lambda_m$, and vectors $\mathbf{u}, \mathbf{v} \in \mathbb{R}^M$ having entries $u_m = \alpha_m^* \eta_m$ and $v_m = \alpha_m^* \lambda_m$.

Spectral analysis. Each diagonal entry satisfies

$$d_m = 1 - \frac{1}{\bar{\alpha}\alpha_m^* - 1} \in (0, 1). \tag{17}$$

By the matrix determinant lemma, the eigenvalues of $\mathbf{A}$ that are not among the d_m are roots of the secular equation

$$f(\mu) \equiv 1 + \sum_{m=1}^{M} \frac{c_m}{d_m - \mu} = 0, \qquad c_m \equiv u_m v_m = (\alpha_m^*)^2 \lambda_m \eta_m. \tag{18}$$

Since $\beta_m > 0$ implies $\eta_m > 0$, all coefficients c_m are strictly positive. Clearing denominators, $f(\mu) = 0$ is equivalent to a degree-M polynomial, so there are at most M roots.

I $\mu = 1$ is always a root. Indeed, $d_m - 1 = -\alpha_m^* \lambda_m = -v_m$, so

$$f(1) = 1 + \sum_m \frac{c_m}{-v_m} = 1 - \sum_m \frac{u_m v_m}{v_m} = 1 - \sum_m u_m = 1 - \sum_m \alpha_m^* \eta_m = 1 - \frac{\bar{\beta}}{\bar{\beta}} = 0.$$

This unit eigenvalue reflects the constraint $\sum_m \alpha_{mt} = 1$ and is projected out on the simplex.

For the remaining roots, f is strictly increasing between consecutive poles ($f'(\mu) = \sum_m c_m/(d_m - \mu)^2 > 0$). Order the poles as $0 < d_{(1)} < \cdots < d_{(M)} < 1$ (the case of repeated poles is addressed below). Since $c_m > 0$:

- $f(\mu) \to -\infty$ as $\mu \to d_{(k)}^+$, and $f(\mu) \to +\infty$ as $\mu \to d_{(k+1)}^-$.

By the intermediate value theorem, each interval $(d_{(k)}, d_{(k+1)})$ contains exactly one root. This gives $M - 1$ roots in $(d_{(1)}, d_{(M)}) \subset (0, 1)$, which together with $\mu = 1$ accounts for all M roots.

When $d_j = d_k$ for some $j \neq k$, the rank-one perturbation shifts at most one copy of the repeated eigenvalue; the remaining copies stay at $d_j \in (0, 1)$ and are eigenvalues of $\mathbf{A}$ directly. The interlacing applies to the remaining distinct poles.

Stability. The eigenvalues of $\mathbf{A}$ on the tangent space $\{\hat{\boldsymbol{\alpha}} : \mathbf{1}^\top \hat{\boldsymbol{\alpha}} = 0\}$ are the $M - 1$ non-unit eigenvalues identified above, all lying in $(0, 1)$. The spectral radius is therefore strictly less than one. □

B.3 Proof of Theorem 2

Define the inverse function ϕ_m by $\alpha_m = \phi_m(z_m)$ where $z_m \equiv \gamma + \beta_m g^w - g_m^A$. Since h is strictly decreasing, so is ϕ_m, and on the BGP:

$$G(g^w) \equiv \sum_m \phi_m(\gamma + \beta_m g^w - g_m^A) = 1.$$

Totally differentiate this with respect to g_m^A:

$$\sum_{m'} \phi'_{m'}(z_{m'})\, \beta_{m'}\, \frac{\partial g^w}{\partial g^A_m} - \phi'_m(z_m) = 0,$$

so

$$\frac{\partial g^w}{\partial g^A_m} = \frac{\phi'_m}{\sum_{m'} \beta_{m'} \phi'_{m'}} \equiv \frac{\phi'_m}{S}. \tag{19}$$

Since all $\phi'_{m'} < 0$ and $\beta_{m'} \geq 0$ (and with $\beta_l = 1 > 0$), both numerator and denominator are strictly negative, giving $\partial g^w / \partial g^A_m > 0$.

For the second part of the statement, let resource efficiency be

$$\mathcal{R} = \sum_{m'} \alpha_{m'} g^\kappa_{m'} = \gamma + g^w D - \mathcal{A}$$

where $A \equiv \sum_{m'} \alpha_{m'} g^A_{m'}$. Differentiating,

$$\frac{\partial \mathcal{R}}{\partial g^A_m} = \sum_{m'} \Big[g^\kappa_{m'}\, \frac{\partial \alpha_{m'}}{\partial g^A_m} + \alpha_{m'}\, \frac{\partial g^\kappa_{m'}}{\partial g^A_m} \Big].$$

From $g^\kappa_{m'} = \gamma + \beta_{m'} g^w - g^A_{m'}$, the second factors are

$$\frac{\partial g^\kappa_m}{\partial g^A_m} = \beta_m \frac{\partial g^w}{\partial g^A_m} - 1, \qquad \frac{\partial g^\kappa_{m'}}{\partial g^A_m} = \beta_{m'} \frac{\partial g^w}{\partial g^A_m} \;\; (m' \neq m).$$

And from $\alpha_{m'} = \phi_{m'}(z_{m'})$,

$$\frac{\partial \alpha_m}{\partial g^A_m} = \phi'_m \Big(\beta_m \frac{\partial g^w}{\partial g^A_m} - 1 \Big), \qquad \frac{\partial \alpha_{m'}}{\partial g^A_m} = \phi'_{m'}\, \beta_{m'} \frac{\partial g^w}{\partial g^A_m} \;\; (m' \neq m).$$

Collecting terms, we have

$$\frac{\partial \mathcal{R}}{\partial g^A_m} = \frac{\partial g^w}{\partial g^A_m} \sum_{m'} g^\kappa_{m'}\, \beta_{m'} \phi'_{m'} + D\, \frac{\partial g^w}{\partial g^A_m} - g^\kappa_m \phi'_m - \alpha_m. \tag{20}$$

With $h(u) = \log(\delta u/(u-1))$, we have $h'(u) = -1/[u(u-1)]$, so

$$\phi'_m(z_m) = \frac{1}{h'(\bar{\alpha}\alpha_m) \cdot \bar{\alpha}} = \frac{-(\bar{\alpha}\alpha_m - 1)^2}{\delta \bar{\alpha}} = \frac{-\mu_m^2}{\delta \bar{\alpha}}$$

where we define

$$\mu_m \equiv \bar{\alpha}\alpha_m - 1 > 0.$$

Note that $g_m^\kappa = h(\mu_m + 1) = \delta/\mu_m + \delta - 1$. We can also derive

$$
\begin{aligned}
S &= -\frac{1}{\delta\bar{\alpha}} \sum_{m'} \beta_{m'} \mu_{m'}^2 \\
\sum_{m'} g_{m'}^\kappa \beta_{m'} \phi'_{m'} &= -\frac{1}{\bar{\alpha}} \sum_{m'} \beta_{m'} \mu_{m'} - \frac{(1-\delta)}{\delta\bar{\alpha}} \sum_{m'} \beta_{m'} \mu_{m'}^2 \\
D &= \frac{1}{\bar{\alpha}} \sum_{m'} \beta_{m'} (\mu_{m'} + 1)
\end{aligned}
$$

Combing these in (20), gives

$$
\frac{\partial \mathcal{R}}{\partial g_m^A} = \frac{\phi'_m}{S} \left(\sum_{m'} g_{m'}^\kappa \beta_{m'} \phi'_{m'} + D \right) - g_m^\kappa \phi'_m - \alpha_m,
$$

where we have used (19). Evaluate the first term

$$
\begin{aligned}
\frac{\phi'_m}{S} \left[\sum g_{m'}^\kappa \beta_{m'} \phi'_{m'} + D \right] &= \frac{-\mu_m^2/(\delta\bar{\alpha})}{-\sum \beta_{m'} \mu_{m'}^2/(\delta\bar{\alpha})} \cdot \left[\frac{\sum \beta_{m'}}{\bar{\alpha}} - \frac{(1-\delta)\sum \beta_{m'} \mu_{m'}^2}{\delta\bar{\alpha}} \right] \\
&= \frac{\mu_m^2}{\sum \beta_{m'} \mu_{m'}^2} \cdot \frac{1}{\bar{\alpha}} \left[\sum \beta_{m'} - \frac{(1-\delta)}{\delta} \sum \beta_{m'} \mu_{m'}^2 \right]
\end{aligned}
$$

For the remaining terms

$$
\begin{aligned}
-g_m^\kappa \phi'_m - \alpha_m &= -\left(\frac{\delta}{\mu_m} + \delta - 1 \right) \cdot \frac{-\mu_m^2}{\delta\bar{\alpha}} - \frac{\mu_m + 1}{\bar{\alpha}} \\
&= \frac{1}{\bar{\alpha}} \left(\mu_m + \frac{(\delta-1)}{\delta} \mu_m^2 \right) - \frac{\mu_m + 1}{\bar{\alpha}} \\
&= \frac{1}{\bar{\alpha}} \left(\frac{(\delta-1)}{\delta} \mu_m^2 - 1 \right).
\end{aligned}
$$

So we can write

$$\begin{aligned}
\frac{\partial \mathcal{R}}{\partial g_m^A} &= \frac{1}{\bar{\alpha}}\left[\frac{\mu_m^2 \sum \beta_{m'}}{\sum \beta_{m'}\mu_{m'}^2} - \frac{(1-\delta)}{\delta}\cdot\frac{\mu_m^2 \sum \beta_{m'}\mu_{m'}^2}{\sum \beta_{m'}\mu_{m'}^2} - \frac{(1-\delta)}{\delta}\mu_m^2 - 1\right] \\
&= \frac{1}{\bar{\alpha}}\left[\frac{\mu_m^2 \sum \beta_{m'}}{\sum \beta_{m'}\mu_{m'}^2} - \frac{(1-\delta)}{\delta}\mu_m^2 - \frac{(1-\delta)}{\delta}\mu_m^2 - 1\right]. \\
&= \frac{\mu_m^2}{\bar{\alpha}}\cdot\frac{\sum \beta_{m'}}{\sum \beta_{m'}\mu_{m'}^2} - \frac{1}{\bar{\alpha}} \\
&\equiv \frac{1}{\bar{\alpha}}\left[\frac{\mu_m^2}{\overline{\mu^2}} - 1\right] \\
&= \frac{1}{\bar{\alpha}}\cdot\frac{\mu_m^2 - \overline{\mu^2}}{\overline{\mu^2}}.
\end{aligned}$$

where we define

$$\overline{\mu^2} \equiv \frac{\sum \beta_{m'}\mu_{m'}^2}{\sum \beta_{m'}}$$

as the β_m-weighted mean of the μ_m. Since $\mu_m = \bar{\alpha}\alpha_m - 1$ is increasing in the expenditure share, this will only be positive for materials with a μ_m higher than the root-mean-square. If $M \geq 2$ BGP shares are not identical across all factors with $\beta_m > 0$, then the resource drag holds for at least one material.